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Probability of Tropical Cyclone Induced Winds at Cape Kennedy

Technical Memorandum WBTM SOS-1

U.S. DEPARTMENT OF COMMERCE / ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

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U. S. DEPARTMENT OF COMMERCE

ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION

WEATHER BUREAU

Weather Bureau Technical Memorandum SOS-1

PROBABILITY OF TROPICAL CYCLONE INDUCED WINDS AT CAPE KENNEDY

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SPACE OPERATIONS SUPPORT DIVISION

SILVER SPRING, MD.
June 1968

ABSTRACT

A statistical technique is developed for estimating the climatological probability that an existing tropical cyclone will produce sustained 35-knot winds at Cape Kennedy. Probabilities are computed for specific times and for various time intervals extending to seven days. The technique is developed initially considering only the storm's location, then expanded to take into account its antecedent path. Two classes of storms are processed separately: (1) Those originating over the Atlantic Ocean or the eastern Caribbean Sea, and (2) those originating over the western Caribbean Sea or the Gulf of Mexico. The technique can be adapted for wind speeds of other threshold values and for other coastal locations which may be affected by tropical cyclones.

A condensation of this paper was presented at the Fifth Space Congress, sponsored by the Canaveral Council of Technical Societies, Cocoa Beach, Florida, March 11-14, 1968.

INTRODUCTION

This study was undertaken by the Spaceflight Meteorology Group (SMG), Weather Bureau, ESSA, in response to a request from the National Aeronautics and Space Administration (NASA), Kennedy Space Center, to provide quantitative estimates of the likelihood of Cape Kennedy experiencing critical winds associated with tropical storms or hurricanes. Since the time required to return the Saturn V - Apollo space vehicle to the Vehicle Assembly Building at certain stages of launch preparation exceeds the period for which forecasts are issued, it is necessary to rely on climatology for periods exceeding 72 hours.

The Weather Bureau's Spaceflight Meteorology Group, through funds transferred from the NASA Office of Manned Space Flight, provides the primary meteorological support for the NASA manned spaceflight program. The authors are members of the Miami Section of SMG, collocated with the ESSA Weather Bureau's National Hurricane Center at the University of Miami.

The problem posed to the Spaceflight Meteorology Group was threefold: (1) What is the probability of critical winds at Cape Kennedy during periods of various specified lengths during the hurricane season without regard to the current tropical cyclone situation? (2) What is the probability at a specified time of an existing tropical storm or hurricane producing critical winds at Cape Kennedy, and the total probability of an existing tropical storm or hurricane producing critical winds within a specified period of time? (3) What is the probability of an existing tropical storm or hurricane producing critical winds at Cape Kennedy, considering the storm's antecedent motion?

In this report a critical wind is defined as a one-minute average wind of 35 knots at anemometer level (10 meters at the Cape Kennedy weather station) produced by a tropical storm or hurricane. Assuming the gust factors usually associated with winds of this magnitude (1.4 or slightly higher), 35-knot one-minute winds would be accompanied by gusts approaching 50 knots. Tropical storms or hurricanes will be referred to jointly in this paper as tropical cyclones or simply as storms.

SELECTION OF CASES

Data on all tropical cyclones occurring in the Atlantic, Gulf of Mexico, or the Caribbean after the year 1885 were computer processed to determine if they were likely to have produced critical winds at Cape Kennedy. The University of Miami IBM 7040 computer was used for this and, wherever feasible, for other computational aspects of this study. Since the period of surface wind records at Cape Kennedy is much shorter than the period of record of tropical cyclones, a procedure was devised for the selection of storms likely to have produced critical winds at this site. The following regression equation relating radius of 35-knot winds to maximum wind in the storm was developed and tested on all tropical cyclones passing within 150 miles of Cape Kennedy during the ten years of overlapping period of record of Cape Kennedy surface winds and tropical cyclones, 1957-1966:

$$R = .6\, W_{max} + 30 \tag{1}$$

where R = radius of 35 knot winds in nautical miles

W_{max} = estimated mean maximum wind in the storm in miles per hour[1] for given day.

Maximum winds in each tropical cyclone were estimated for each day of the storm's existence by the National Weather Records Center for periods subsequent to 31 July 1899. During the 14 years of record prior to that date, maximum winds in storms approaching Cape Kennedy were estimated by the writers according to whether the storms were classified as tropical storms or hurricanes, and whether they approached from the land or the sea.

Details of the storm-selection technique are shown in Figures 1 and 2. Figure 1 presents the logic in terms of a computer flow chart, while Figure 2 presents a schematic representation of a fictitious case. Referring to Figure 1, the initial computer decision as to whether a storm ever moved west of 75°W or north of 20°N immediately eliminates from further consideration a large percentage of the storms which obviously never affected Cape Kennedy. Next, a linear interpolation between the card-punched 0000GMT and 1200GMT storm positions gives 3-hourly storm positions for 0300GMT, 0600GMT and 0900GMT while interpolation between the 1200GMT and 0000GMT

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[1] miles per hour was chosen as the unit of wind speed because the computer card deck was punched in this unit.

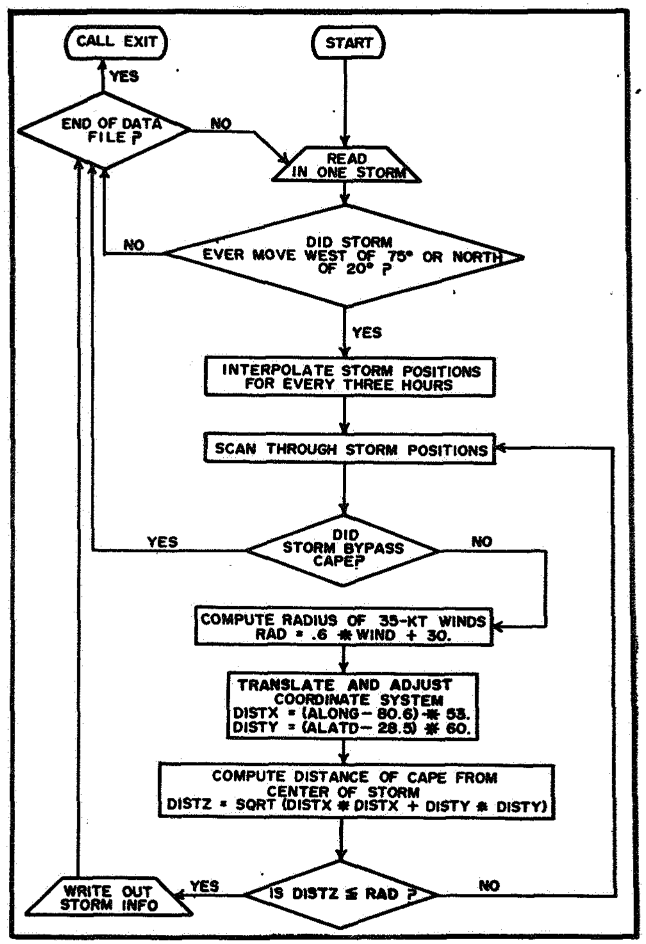


Figure 1: Computer flow chart showing storm selection technique.

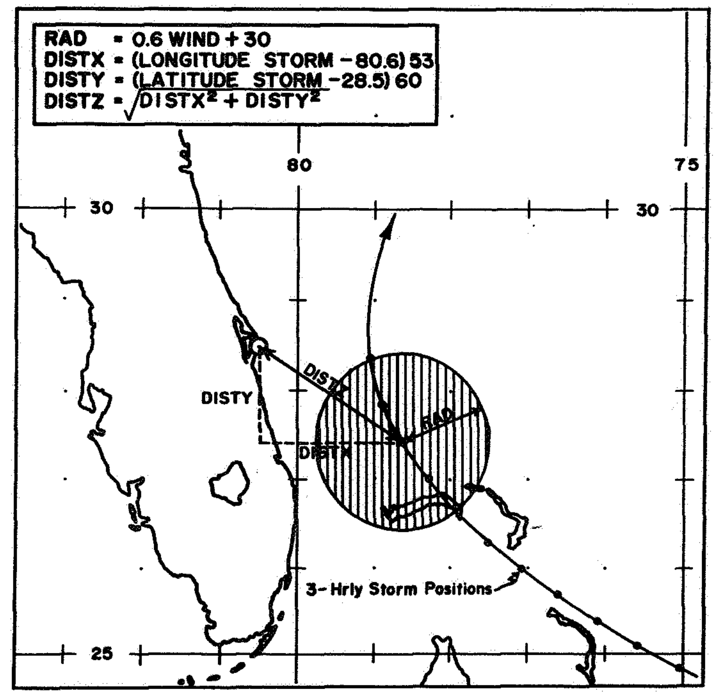


Figure 2: Schematic illustration showing storm selection technique.

card-punched positions gives intermediate positions for 1500GMT, 1800GMT and 2100GMT for each day of the storm's existence. The computer decision as to whether a storm bypassed Cape Kennedy removes from further consideration those storms which were not filtered out by the first screening but which are now moving away from Cape Kennedy after having moved to a minimum distance from the Cape without producing critical winds. The actual decision as to whether the storm ever produced critical winds at the site depends on whether distance Z (DISTZ, as defined in Figure 2) is equal to or less than the radius of 35-knot winds as defined by equation (1). The constant 53 in the expression for DISTX is simply the length, in nautical miles, of one degree of longitude at the latitude of Cape Kennedy. The term WIND as used on both Figures 1 and 2 refers to the mean maximum wind near the center of the storm on a given day.

It is realized that this method of selection of storms affecting Cape Kennedy is somewhat arbitrary. Undoubtedly in some hurricanes sustained winds in excess of 35 knots will extend much farther from the storm center than equation (1) indicates, while in some minimal tropical storms the radius of 35-knot winds would be smaller. It is true also in general that asymmetry in the wind field is observed in most storms, which is in turn a function of the intensity of the storm, its direction of movement, and the surrounding synoptic features. However, it is believed that in dealing with mean conditions where large numbers of storms are considered, the method outlined above correctly identifies most of the storms that have produced 35-knot sustained winds at Cape Kennedy.

Equation (1) yields values for radii of 35-knot winds not greatly different from those obtained from other models, for example, Jelesniaski (1966) and Hughes (1952). In any case, it is believed that this method of selection is superior to considering all storms passing within a fixed distance from the station.

The paths of all tropical storms, 1886-1966, which were calculated to have produced critical winds at Cape Kennedy according to the above criteria are shown in Figure 3.

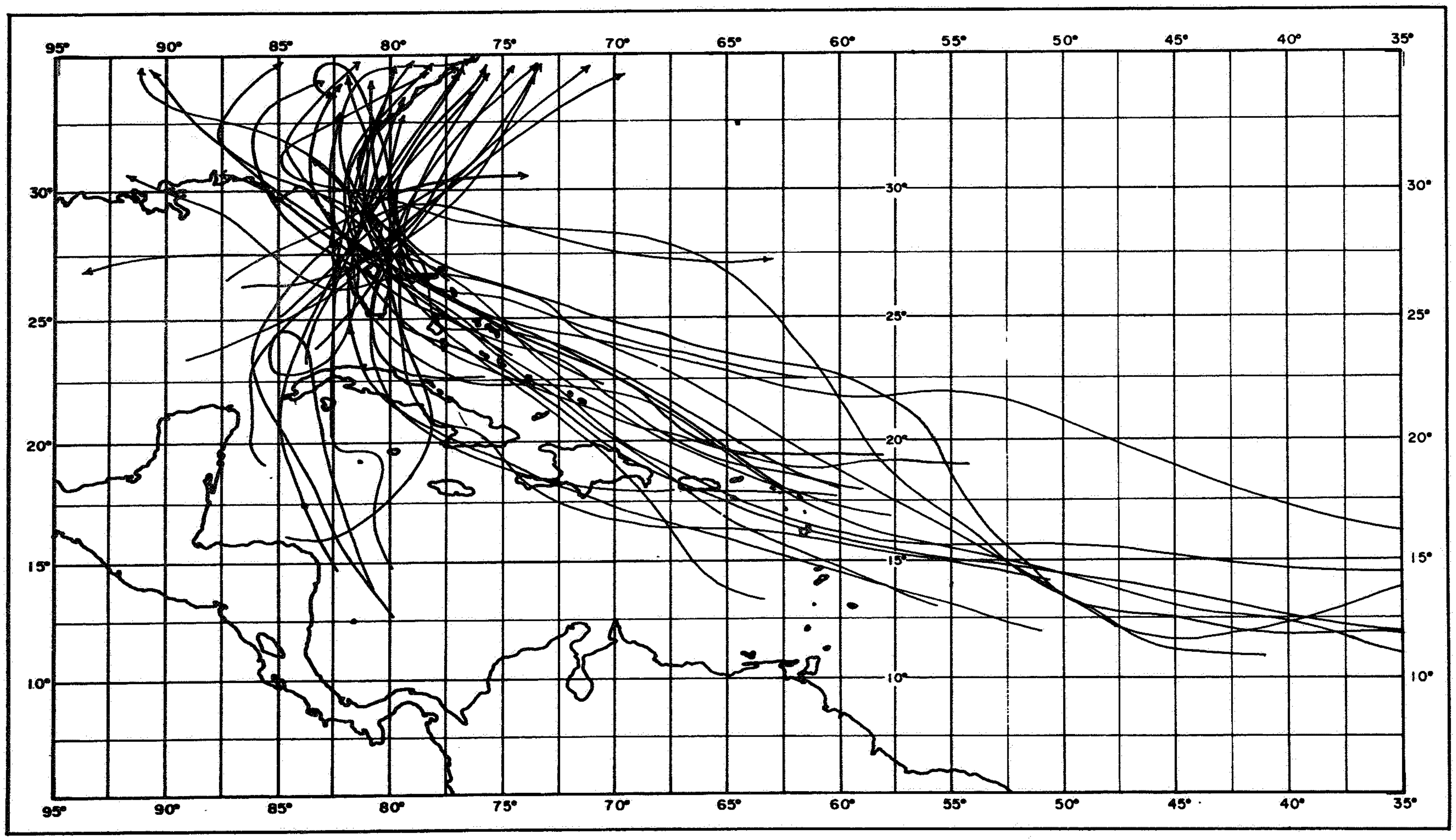


Figure 3: Tracks of tropical storms or hurricanes which produced critical winds at Cape Kennedy, 1886-1966.

PROBLEM 1

The initial problem was to determine the average frequency of critical winds at Cape Kennedy without regard to the current existence of any tropical cyclones.

Table 1 lists all the tropical cyclones which were computed to have produced critical winds at Cape Kennedy 1886-1966. These data are presented in graphical form in Figure 4. In all there were 36 such occurrences over the span of 81 years giving a mean of 0.44 storms per year. However, in the years 1887, 1891, 1893, 1928, 1933, and 1964 there were two occurrences each, leaving 30 years out of a possible 81 during which critical winds were observed at least once. The observed percentage frequency of one or more occurrences of the critical wind condition is therefore 0.37 or 37% of the years. In example 1, page 57, illustrating the use of the figures and tables contained within this report, it is shown that the observed frequencies closely approximate the probabilities computed by fitting the data to a Poisson distribution, where the sample mean (0.44) is used as the Poisson parameter.

Figure 5 stratifies the tropical cyclone data into calendar months, while Figure 6 further stratifies the data into calendar weeks (week one, January 1-7, etc.). As expected, both figures show the typical late summer and autumn tropical cyclone maximum but the latter figure suggests the possibility of some minor variations within the season itself. These intra-seasonal variations are depicted in greater detail in Figure 7. The frequencies on this latter figure are based on a 3-week moving average of the daily critical wind occurrences at Cape Kennedy over the period of record. For example, the percentage frequency of 0.76 on October 16 indicates that between October 6 and October 26, 1886 through 1966 (a total of 1701 days), critical winds were observed at Cape Kennedy on 13 days. (.0076 x 1701 = 13).

Between May 18 and November 8, Figure 7 shows that there are four peaks to the tropical cyclone season at Cape Kennedy. A small, almost insignificant maximum occurs in early June, while other, better defined peaks are seen to occur in early August, early September, and finally in mid-October. Minimum values occur during the first two weeks in July, mid-August, and late September.

Table 1. Tropical storms or hurricanes computed to have produced critical winds at Cape Kennedy 1886-1966. T-0 (to the closest three hours) refers to the time of initial onset of critical winds. Positions are given in degrees of latitude north and longitude west. Storm number corresponds to those given in WEABUR Technical Paper No. 55. Storm type refers to classification at T-24 hours. Categories A, B, and C refer to early-, mid-, and late-season storms respectively.

Year	Month & Day	Time (EST)	Storm Number	Storm Type	Category	Storm position prior to striking Cape (times are in hours) T-0	T-24	T-48	T-72	T-96	T-120	T-144	T-168
1887	Aug 20	0400	4	H	B	28.2 79.3	26.2 78.2	25.6 74.5	24.5 70.9	23.8 67.3	22.5 62.2		
1887	Oct 29	1900	14	TS	C	27.9 80.9	24.0 87.0						
1891	Oct 7	1000	7	TS	B	27.8 80.0	23.0 80.8	19.8 77.1	18.5 72.9	18.0 67.9	17.8 63.8	17.8 60.4	
1891	Oct 10	0100	8	TS	C	29.1 80.7	25.8 83.0	21.8 84.8	18.6 84.2	15.4 82.8			
1892	Oct 25	0100	9	TS	C	29.4 81.0	28.0 84.2	26.0 88.0	24.3 90.5				
1893	Aug 26	2200	6	H	B	27.8 79.1	25.3 76.1	23.8 69.6	23.0 65.6	22.3 60.5	21.9 54.9	20.0 48.0	17.6 40.6
1893	Oct 12	0700	9	H	B	27.6 79.0	26.1 75.3	25.0 71.3	24.1 67.6	23.1 64.2	22.6 60.0	21.9 58.8	20.3 56.5
1894	Sep 25	1600	3	H	B	27.1 81.7	23.6 81.6	20.2 77.3	18.8 72.2	16.9 67.5	15.0 61.9	13.7 57.4	12.7 53.6
1896	Oct 9	0400	5	H	C	27.4 80.6	24.5 85.7	23.0 89.8					
1897	Sep 21	0700	3	TS	C	28.3 81.4	24.3 83.8						
1898	Aug 1	1900	1	H	B	27.3 81.0	25.5 75.6						
1899	Aug 13	0700	2	H	B	27.0 79.6	22.2 76.3	20.8 73.4	19.5 69.5	17.9 65.8	16.1 60.5	15.1 54.2	14.0 47.0
1903	Sep 11	1900	3	H	B	26.5 80.0	24.8 77.3	23.3 75.0					
1906	Jun 17	1300	2	H	A	27.5 79.3	24.2 80.9	22.8 78.5	22.6 76.5				
1909	Aug 30	0700	6	TS	B	27.7 80.3	26.0 77.6	24.5 75.0	22.0 70.6	19.6 66.0			
1910	Oct 18	1300	4	H	C	28.3 81.8	24.5 82.5	22.6 84.5	24.4 84.0	22.0 83.3	19.5 83.0	16.3 82.0	13.8 81.0
1915	Aug 1	0400	1	TS	B	28.1 79.9	27.6 76.6						
1921	Oct 25	1900	6	H	C	28.0 81.8	25.2 85.0	21.8 85.9	18.8 83.9	16.8 82.3	14.8 81.2	12.6 80.0	
1926	Jul 27	1900	1	H	B	27.7 80.3	25.5 78.5	23.3 75.1	20.8 71.3	18.0 66.9	15.4 61.5	13.3 55.7	
1928	Aug 8	0400	1	H	B	27.6 80.5	25.5 79.0	23.2 76.0	20.0 71.5	16.0 67.1	12.9 62.8		
1928	Sep 16	2200	4	H	B	26.6 79.8	23.6 75.1	21.0 71.0	18.5 67.2	17.0 63.0	15.7 57.7	15.8 51.3	15.3 44.9
1933	Jul 30	1600	5	H	B	27.4 80.3	22.9 78.0	25.1 75.2	22.3 72.2	19.9 67.8	18.0 62.9		
1933	Sep 4	0400	12	H	B	27.5 80.8	25.2 75.9	22.8 70.2	19.5 64.5	19.5 57.5			
1934	May 28	0400	1	TS	A	27.7 80.4	24.2 82.9						
1937	Aug 30	0100	3	TS	B	28.4 79.9	26.4 78.7	24.8 77.8	24.0 73.4	22.0 68.2	19.8 64.5	18.0 59.0	
1939	Aug 11	1600	2	TS	B	27.5 80.5	25.0 75.6	23.2 71.2	21.2 67.5	18.9 64.0			
1944	Oct 19	0700	11	H	C	28.4 82.1	23.1 82.8	20.7 82.8	19.6 82.3	19.6 80.7	18.6 80.6	17.4 80.8	14.9 80.0
1945	Sep 16	1000	9	H	B	28.4 81.8	24.5 79.1	22.2 74.0	20.1 67.3	19.3 60.5	18.8 54.0		
1947	Sep 17	0400	4	H	B	26.5 79.0	26.6 76.0	25.7 73.2	23.1 68.0	20.9 64.3	18.2 58.7	14.2 51.6	12.2 47.8
1949	Aug 26	1900	2	H	B	26.5 80.1	24.9 77.0	23.0 72.2	19.5 66.2	18.4 61.2			
1950	Oct 18	1000	11	H	C	27.8 81.2	23.5 79.0	19.7 78.7	17.5 80.2	16.2 81.9	16.1 83.5		
1951	Oct 2	1300	8	TS	C	27.9 80.3	26.5 85.7	24.8 87.9	22.8 86.9	19.5 85.3			
1953	Oct 9	1300	12	TS	C	27.5 81.0	23.6 85.8	21.3 86.0					
1960	Sep 10	1900	5	H	B	27.3 81.9	24.2 80.1	22.2 76.9	22.3 72.3	21.8 69.6	20.2 66.3	17.9 62.0	16.0 56.3
1964	Aug 27	1300	5	H	B	27.3 80.3	22.6 79.2	20.6 76.6	17.3 71.0	16.5 66.6	15.7 59.8	14.3 51.4	
1964	Sep 9	0400	6	H	B	29.3 78.9	28.6 75.9	28.2 70.2	27.2 66.0	24.8 62.8	22.3 60.7	19.6 58.8	16.6 54.8

The early season maximum is produced by storms which originate in the Gulf of Mexico or the western Caribbean and generally approach Cape Kennedy from the south or southwest. A rapid increase in the frequency of critical winds can be expected in late July. The reason for the decline to a minimum in mid-August is not clear and may be due simply to the relatively few cases available for analysis. It was noted, however, that most of the storms that comprise the early August maximum originated in the 10-degree latitude-longitude

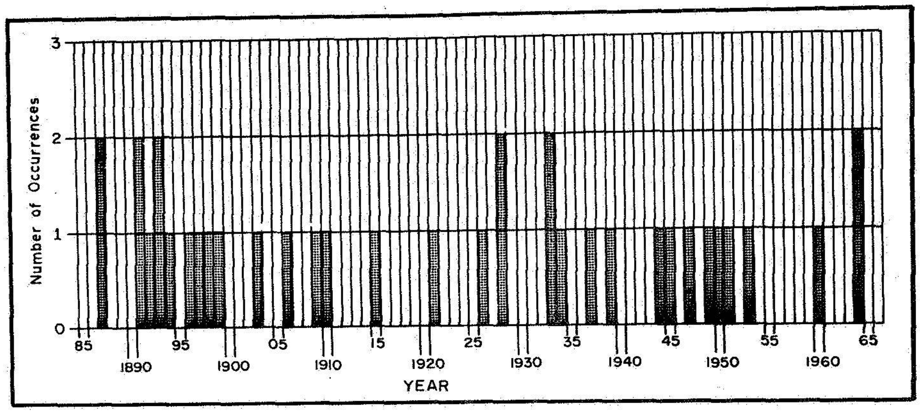


Figure 4: Occurrence of critical winds at Cape Kennedy by year, 1886-1966.

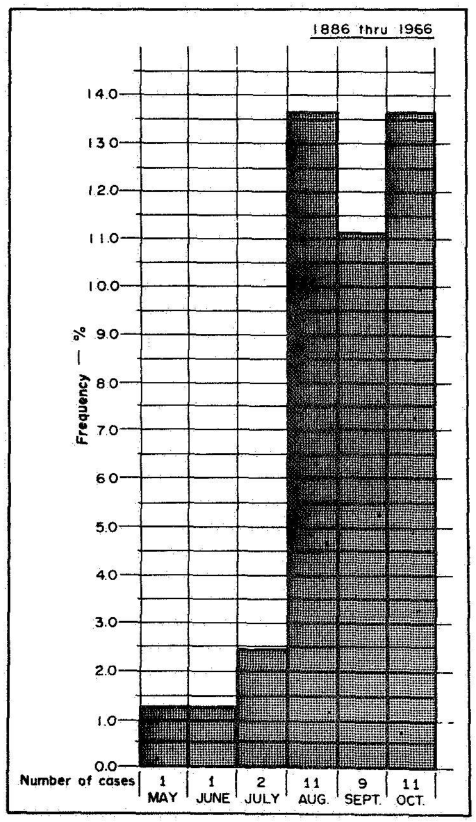


Figure 5: Percent frequency of one or more occurrences of critical wind speed at Cape Kennedy during specified months.

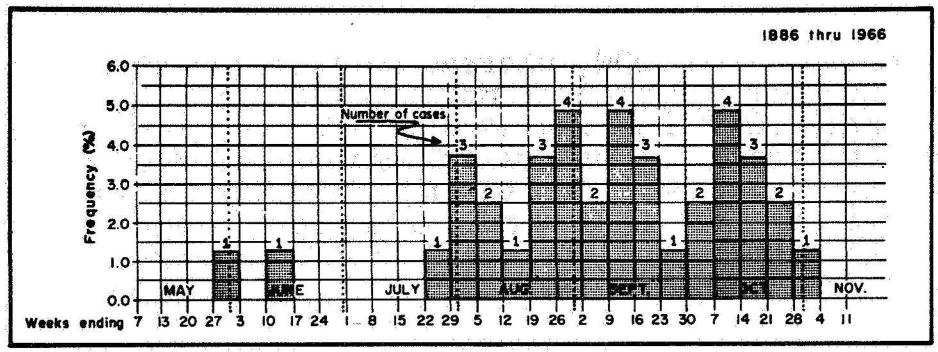


Figure 6: Percent frequency of one or more occurrences of critical wind speed at Cape Kennedy during specified weeks.

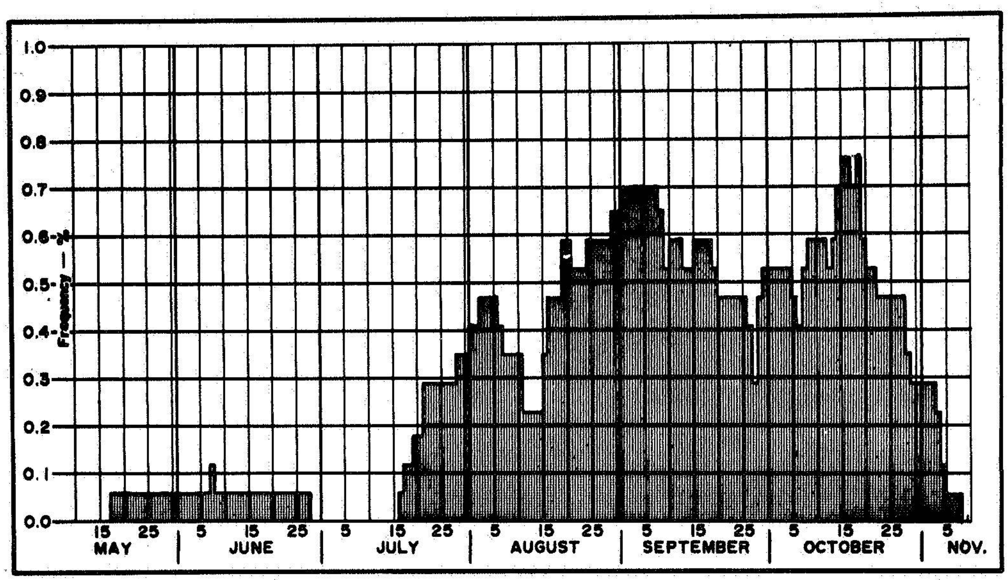


Figure 7: Percent frequency of critical wind speed occurrence at Cape Kennedy on any given date based on 3-week moving average.

box centered at 15N, 60W, whereas most of the storms that comprise the early September maximum originated either in the 10-degree latitude-longitude box five degrees farther north or traversed the entire Atlantic Ocean from off the coast of Africa. The late season maximum in mid-October has a sound physical basis and, as pointed out by Cry (1965), is produced by tropical cyclones that form over the western Caribbean Sea or Gulf of Mexico during that period.

PROBLEM 2

The second problem was to determine the instantaneous and cumulative probabilities of an existing tropical storm producing critical winds at Cape Kennedy within specified periods of time.

The location of all tropical cyclone centers calculated to have produced critical winds were plotted at 24-hour intervals beginning with the time of onset of these winds at Cape Kennedy and working backward seven days, or to the origin of the storm if it had existed less than seven days. An analysis of these plotted positions revealed two distinct source regions for storms which eventually affected Cape Kennedy. One source region was the Atlantic and extreme northeastern Caribbean, while the other was the Gulf of Mexico and western Caribbean. It was necessary, therefore, to process these two groups separately. It was found further that, excepting one May and one June storm during the 81-year period, all of the eastern group of storms occurred during the period July 15 through October 15 (type B or mid-season storms), and all of the western group occurred during the period September 15 through October 31 (type C or late-season storms). Tropical cyclones occurring from May 1 through July 15 were designated type A, or as early season storms, but since only two have produced critical winds at Cape Kennedy during the period of record, they could not be processed according to the scheme to be outlined below.

After plotting these mid and late season storm positions, equi-probability ellipses were computed from the distribution of the storm center locations for each day prior to affecting Cape Kennedy and for each of the two groups of storms, assuming a bivariate normal distribution of the latitude and longitude coordinates. The Kolmogorov-Smirnov one-sample test (Siegel, 1956) was applied to determine that this assumption was reasonable. The differences between the theoretical and actual cumulative probabilities computed did not indicate that this hypothesis should be rejected.

These storm locations and the computed ellipses are shown in Figures 8 through 15. Following convention, storm symbols with open circles are tropical storms while those with darkened circles represent hurricanes. These ellipses depict the theoretical distribution of storms that would be initially producing critical winds at Cape Kennedy in the number of hours or days indicated. That is to say, 90 per cent of such storms should lie within the .90 contour, 10 per cent within the .10 contour, etc. Techniques utilizing probability ellipses applied to a number of geophysical parameters have been described by, among other authors, Rapp and Isnardi (1951), Veigas et al (1959), Crutcher and Baer (1962), Haggard, Crutcher and Whiting (1965), and Groenewoud et al (1967).

It was necessary to compute probability ellipses in order to expand the available data. According to the criteria used in this study, only thirty-six storms affected the Cape Kennedy area during the eighty-one year period of record. The number of storms plotted at 24-hour intervals prior to affecting Cape Kennedy ranged from eight to twenty-three in the Atlantic and from four to eleven in the western Caribbean and the Gulf of Mexico. The ellipses permit redistribution of these storms so that a value can be assigned to each area into which the ellipse is subdivided.

The centroids of the two groups of storms plotted at 24-hour intervals as they approached Cape Kennedy are shown in Figure 16. Note that in the late season group, that is, those originating in the western Caribbean or the Gulf of Mexico, the ellipses were computed for periods extending out to five days only. It was not possible to compute ellipses for six to seven days for storms originating in that area because too few storms were in existence for that length of time prior to their affecting Cape Kennedy. The line connecting the centroids can be considered as the "most critical track" insofar as Cape Kennedy is concerned.

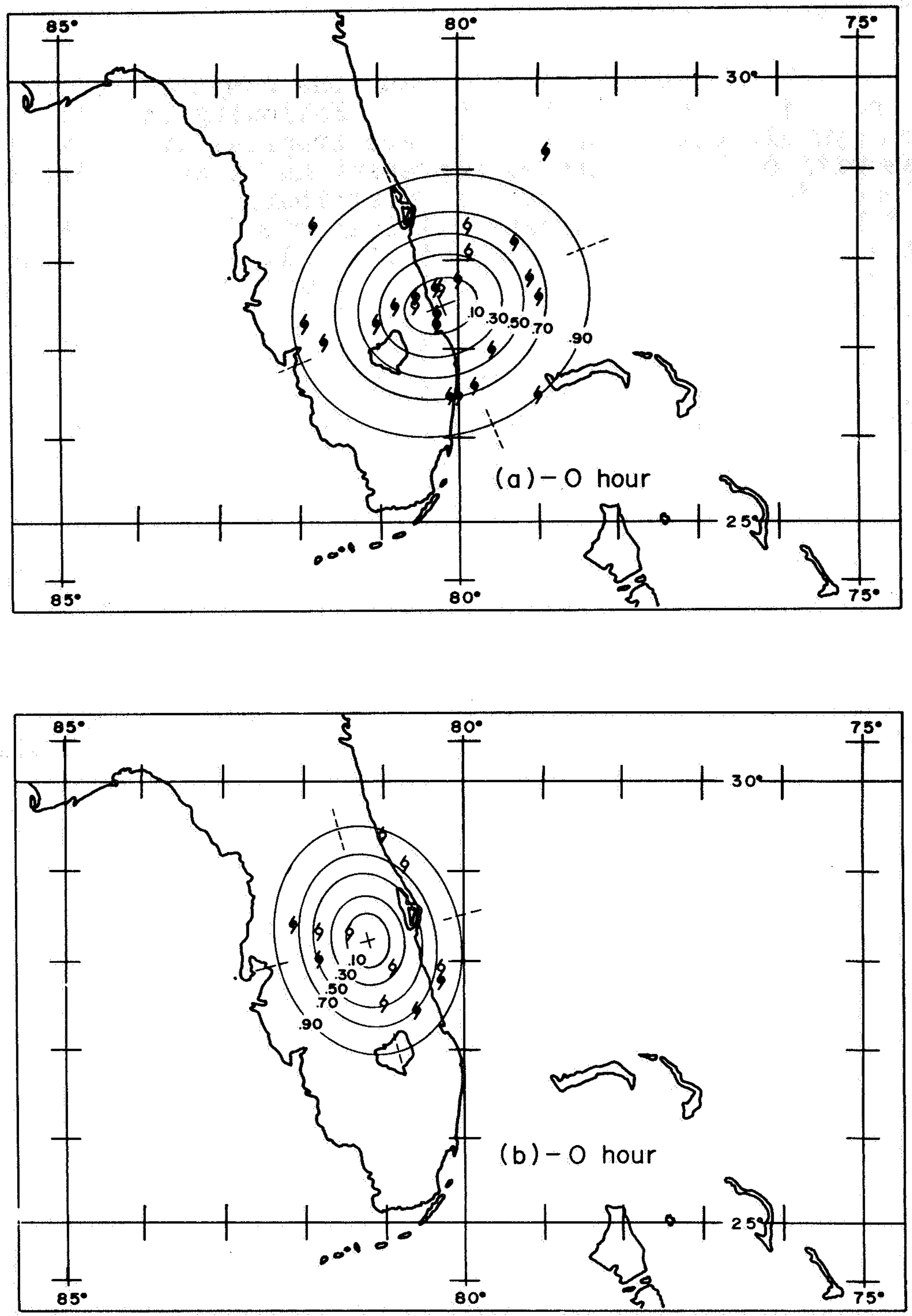


Figure 8: Probability ellipses of the distribution of tropical storms or hurricanes 1886-1966 when they first produced critical winds at Cape Kennedy. (a) Storms having originated in the eastern Caribbean or Atlantic July 15 - October 15, (b) Storms having originated in the western Caribbean or Gulf of Mexico, September 15 - October 31.

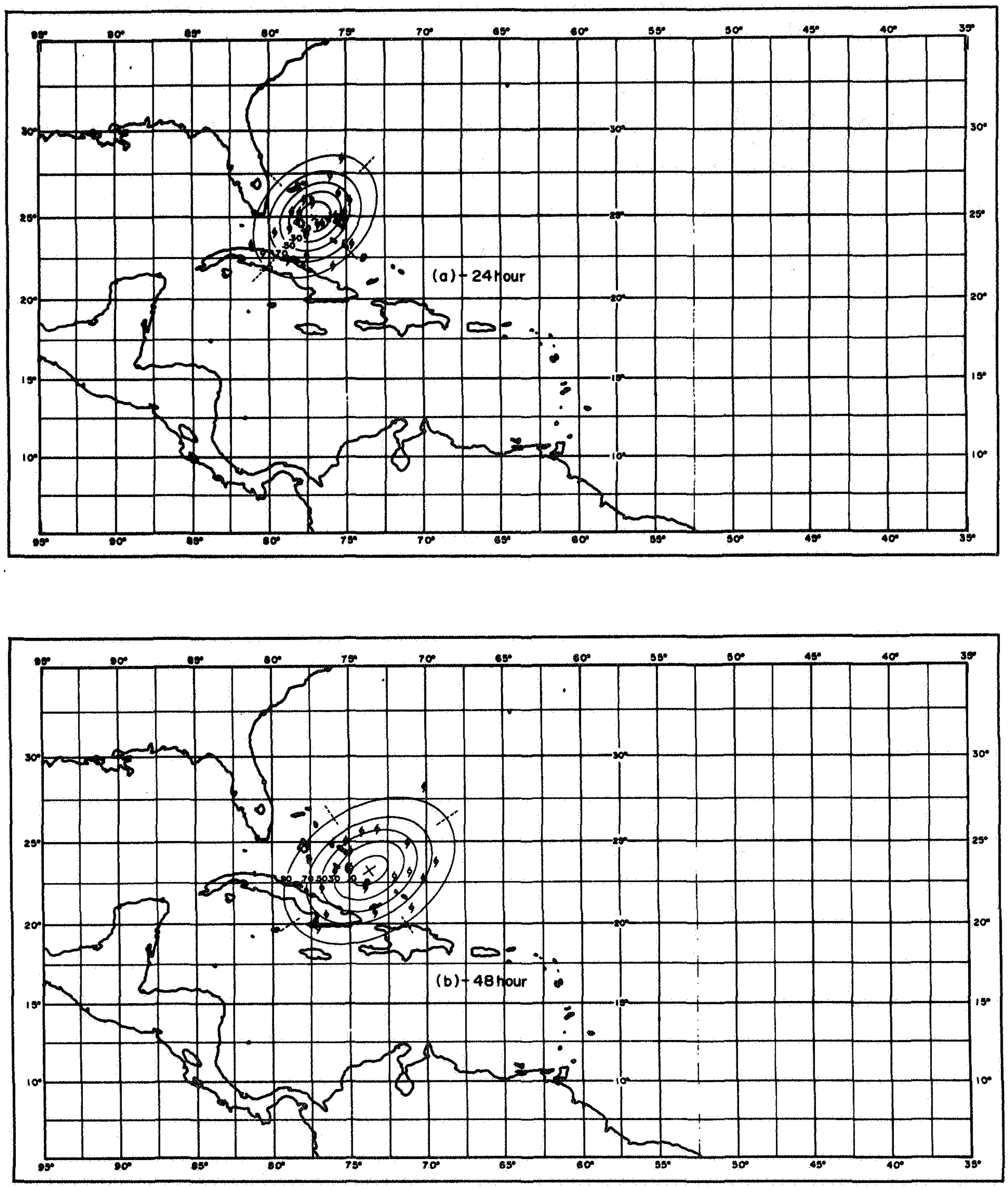


Figure 9: Probability ellipses of the distribution of tropical storms or hurricanes having originated in the eastern Caribbean or Atlantic July 15 - October 15, 1886-1966, which produced critical winds at Cape Kennedy at (a) 24 hours, and (b) 48 hours.

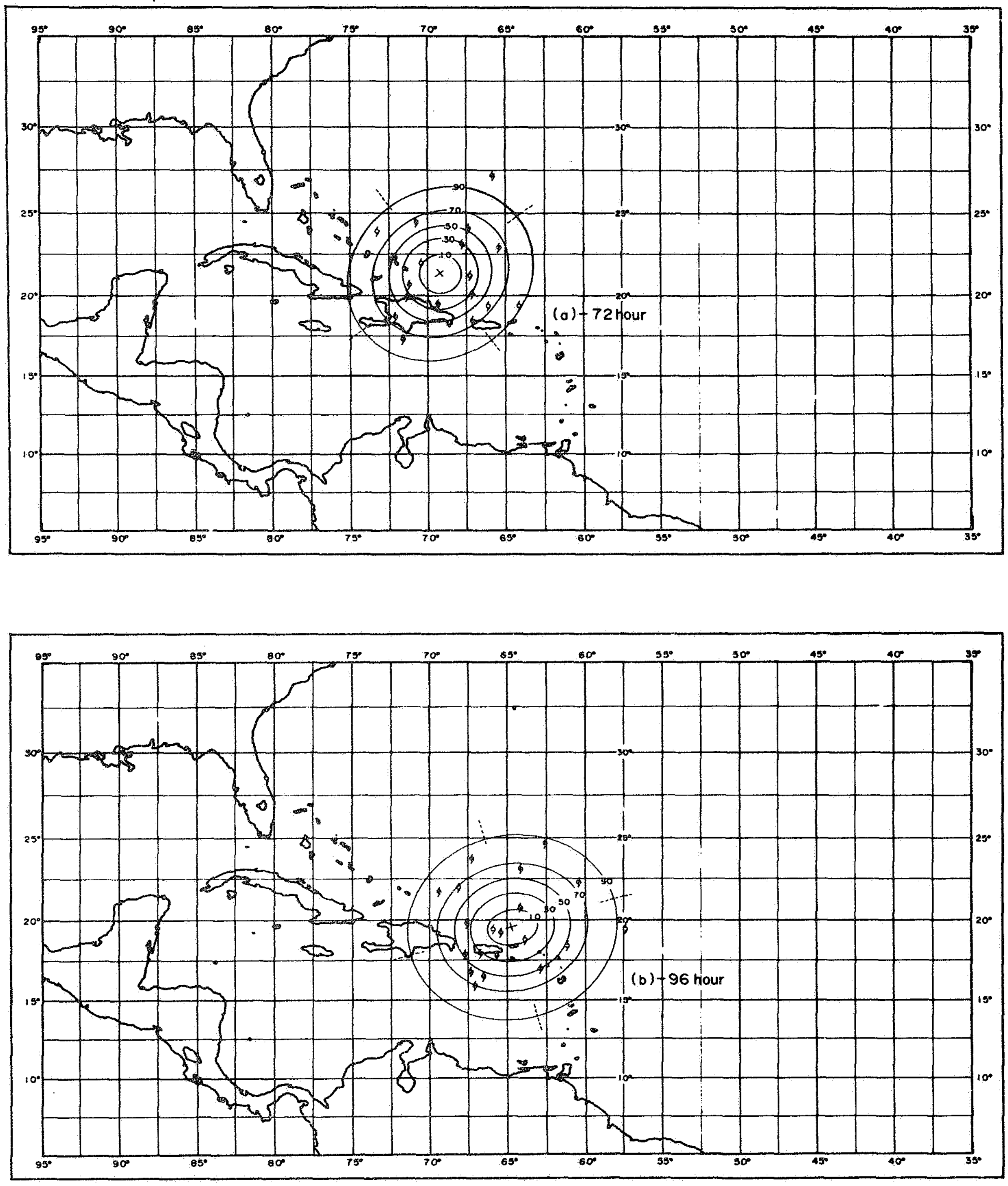


Figure 10: Probability ellipses of the distribution of tropical storms or hurricanes having originated in the eastern Caribbean or Atlantic July 15 - October 15, 1886-1966, which produced critical winds at Cape Kennedy at (a) 72 hours, and (b) 96 hours.

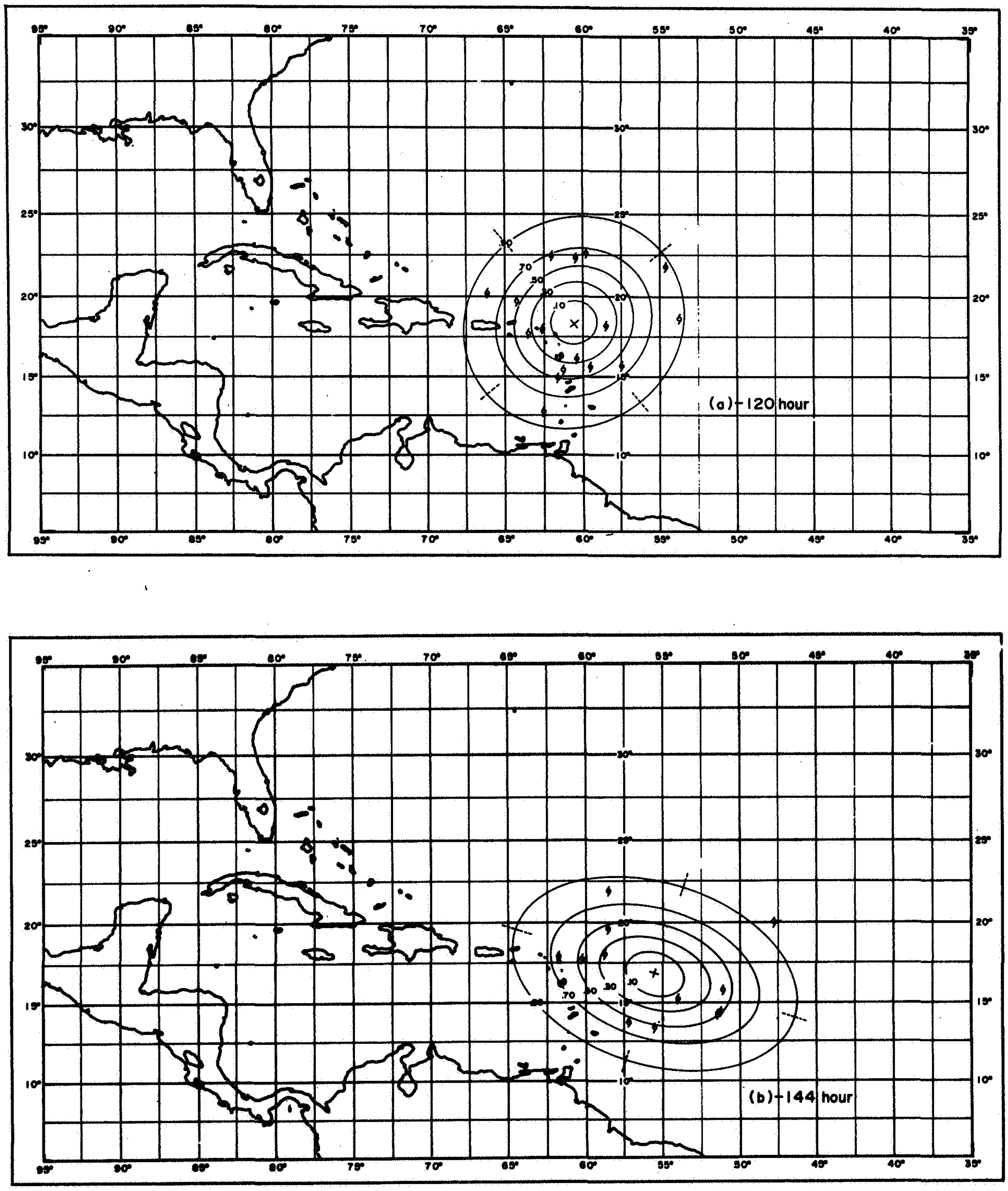


Figure 11: Probability ellipses of the distribution of tropical storms or hurricanes having originated in the eastern Caribbean or Atlantic July 15 - October 15, 1886-1966, which produced critical winds at Cape Kennedy at (a) 120 hours, and (b) 144 hours.

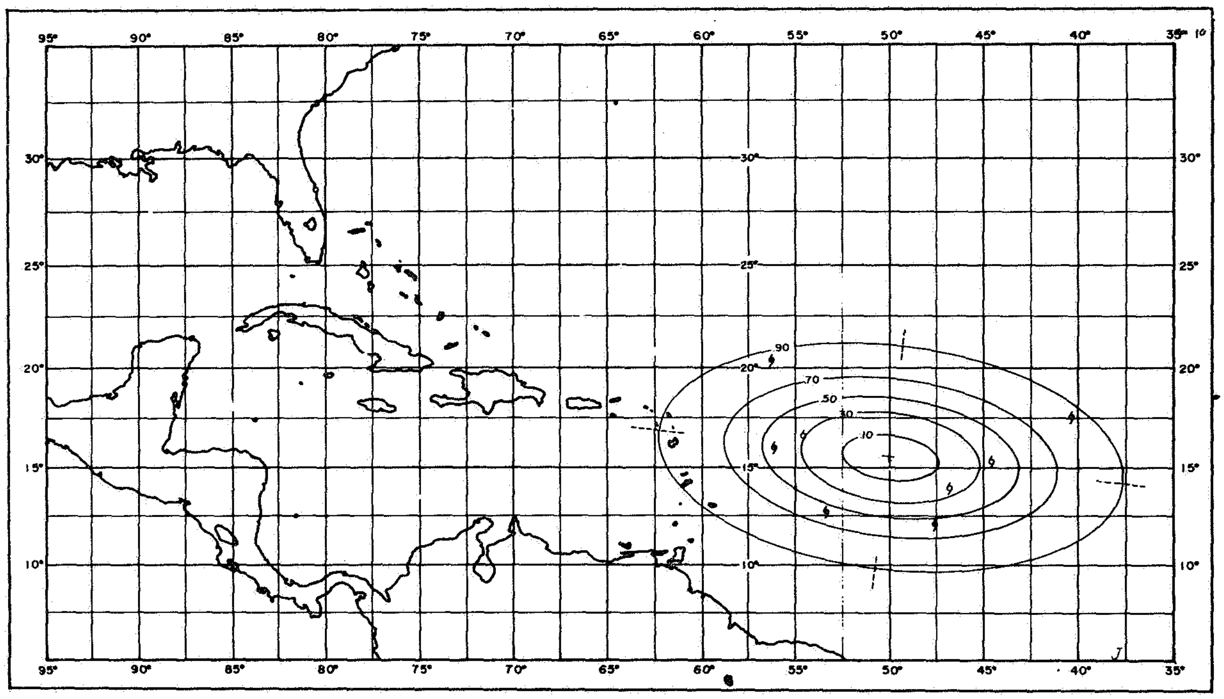


Figure 12: Probability ellipse of the distribution of tropical storms or hurricanes, having originated in the eastern Caribbean or Atlantic July 15 - October 15, 1886-1966, which produced critical winds at Cape Kennedy at the 168th hour.

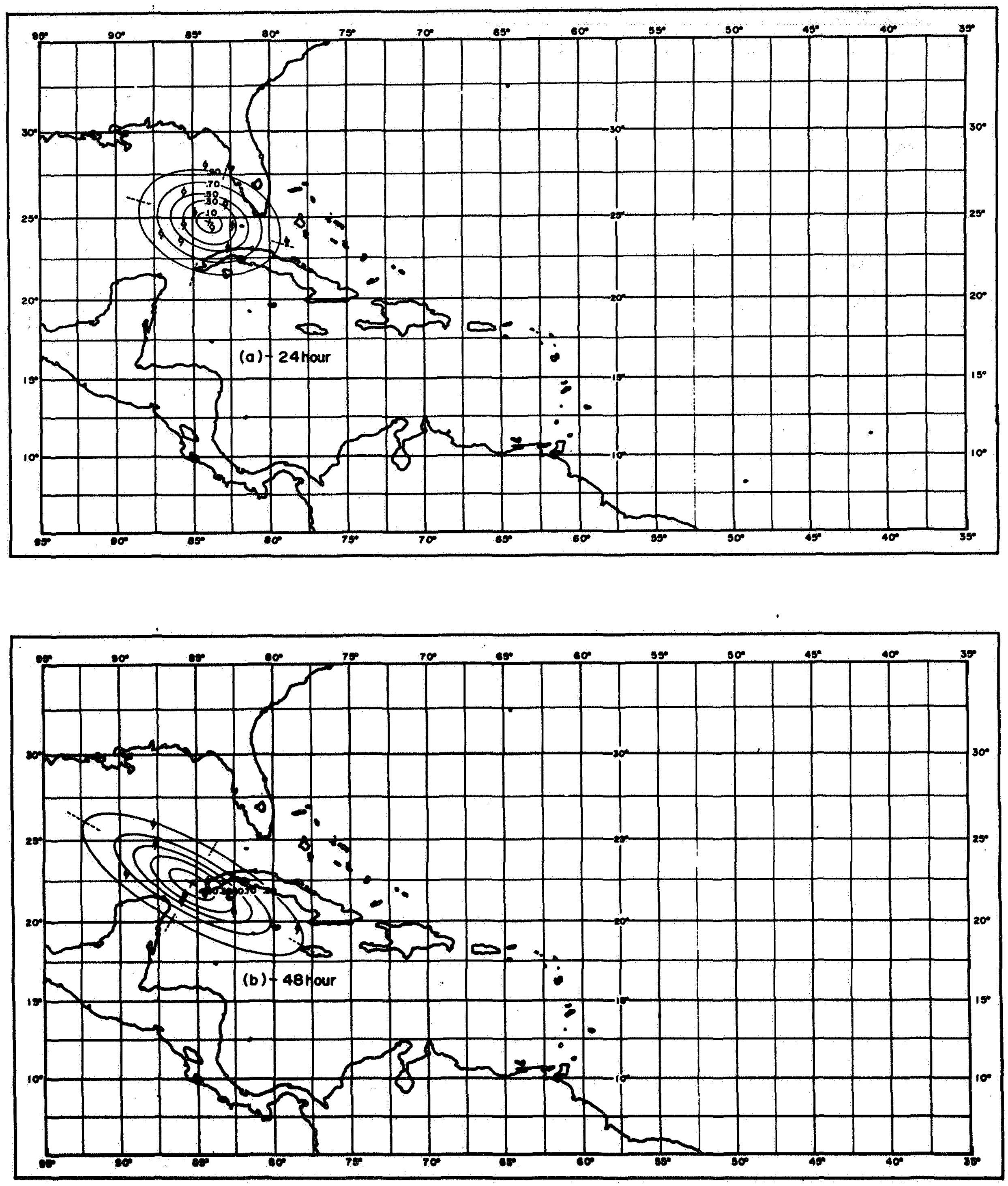
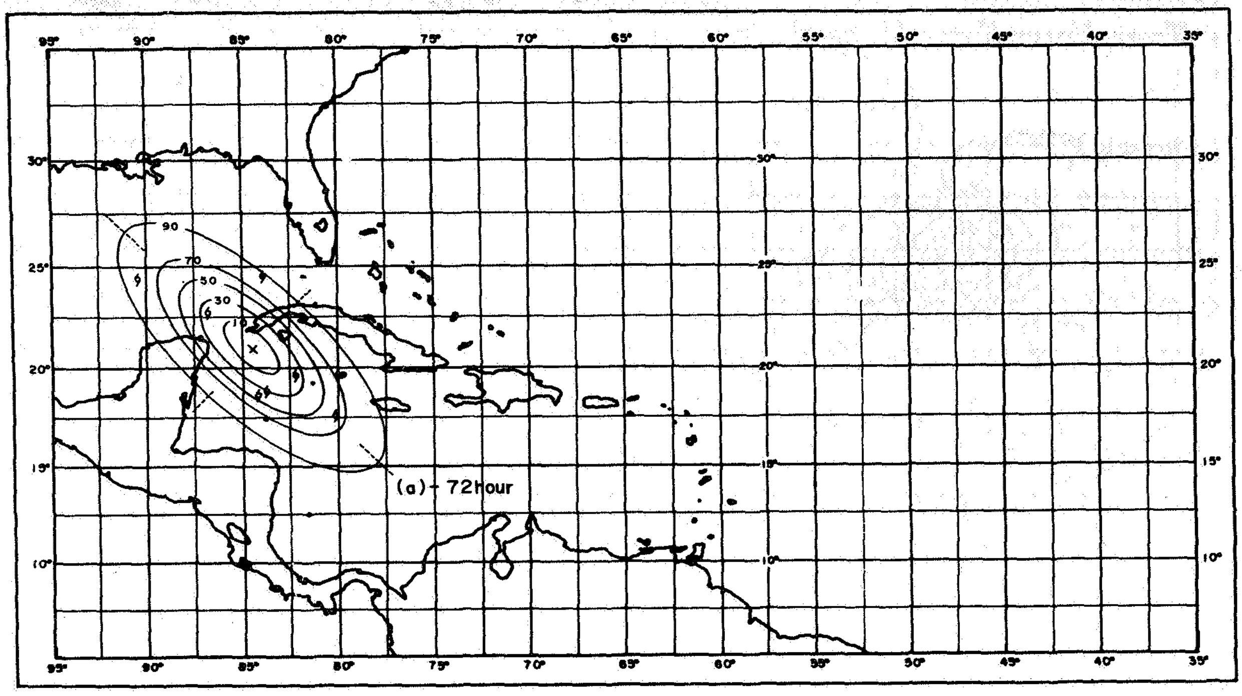


Figure 13: Probability ellipses of the distribution of tropical storms or hurricanes having originated in the western Caribbean or Gulf of Mexico September 15 - October 31, 1886-1966, which produced critical winds at Cape Kennedy at (a) 24 hours, and (b) 48 hours.



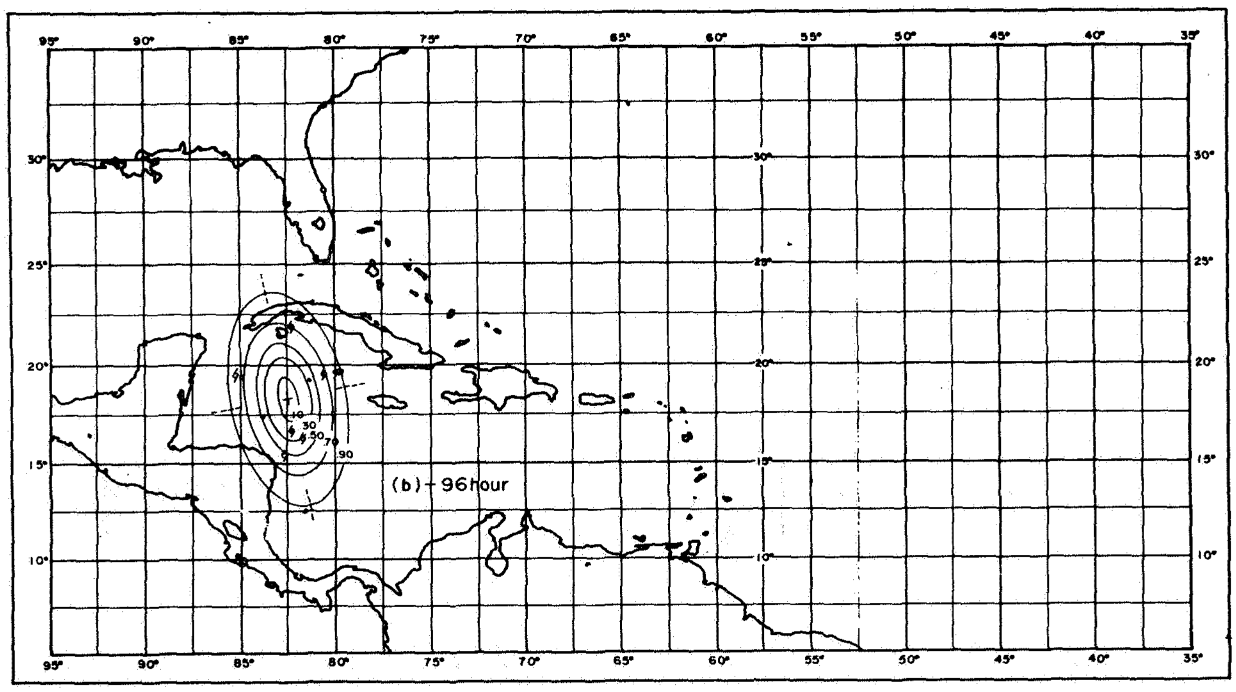


Figure 14: Probability ellipses of the distribution of tropical storms or hurricanes having originated in the western Caribbean or Gulf of Mexico September 15 - October 31, 1886-1966, which produced critical winds at Cape Kennedy at (a) 72 hours, and (b) 96 hours.

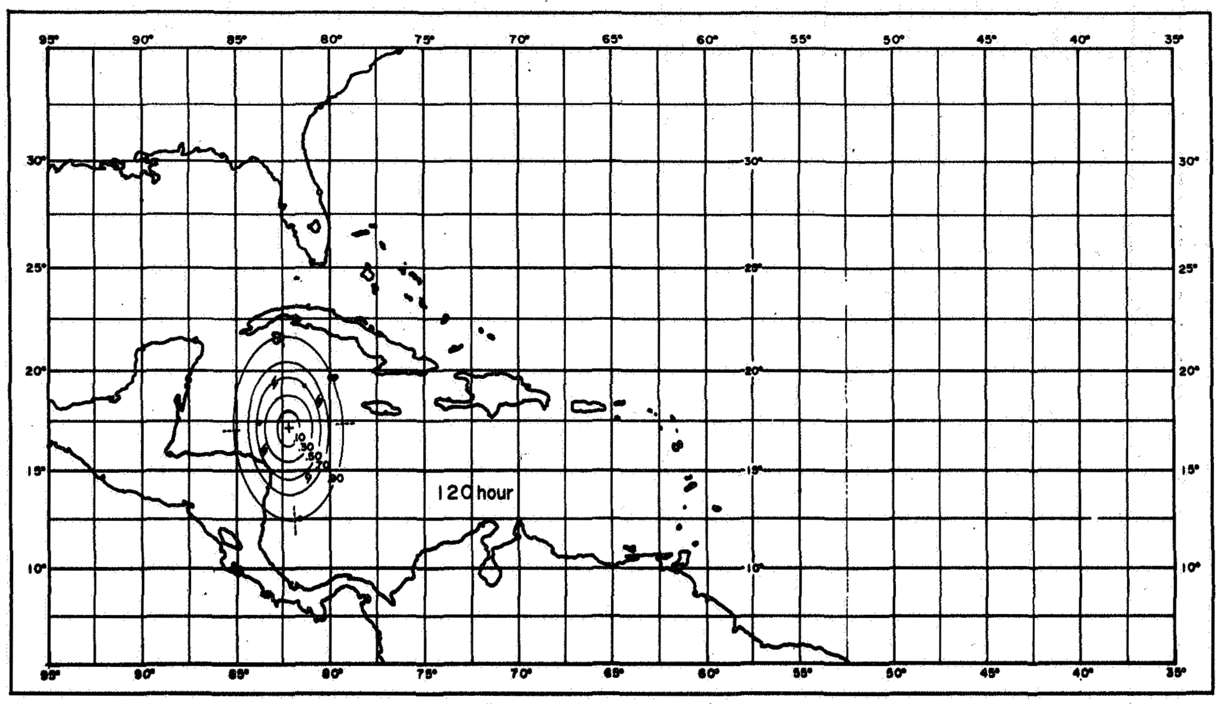


Figure 15: Probability ellipse of the distribution of tropical storms or hurricanes having originated in the western Caribbean or Gulf of Mexico September 15 - October 31, 1886-1966, which produced critical winds at Cape Kennedy at the 120th hour.

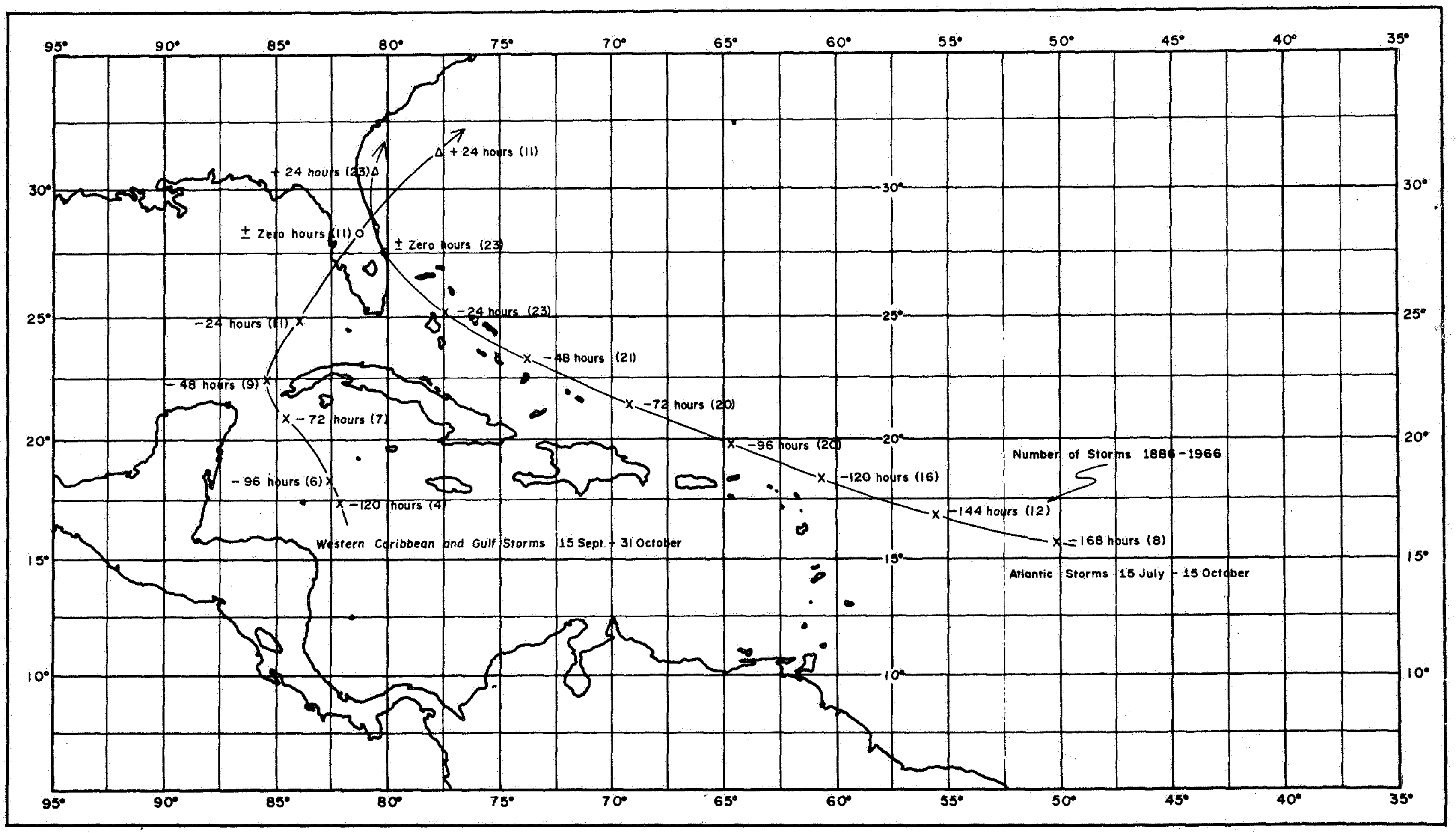


Figure 16: Location of storm center distribution centroids at specified periods prior to (X), initially (o), and after (Δ) producing critical winds at Cape Kennedy.

A brief description of the method of computing the probability ellipses follows.

The bivariate normal probability density function is expressed as

$$f(x,y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho_{xy}^2}}\, e^{-G/2} \tag{2}$$

where G, whose locus in the x,y plane is an ellipse, is

$$G = \frac{1}{1-\rho_{xy}^2}\left[\frac{(x-\mu_x)^2}{\sigma_x^2} - \frac{2\rho_{xy}(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y} + \frac{(y-\mu_y)^2}{\sigma_y^2}\right] \tag{3}$$

(Lindgren, 1962). σ_x and σ_x^2 are the standard deviation and the variance respectively of the x (longitude) coordinate, σ_y and σ_y^2 the standard deviation and the variance of the y (latitude) coordinate, μ_x and μ_y the mean values of the x and y coordinates, and ρ_{xy} is the correlation coefficient between the x and y coordinates of the distribution. In making computations from actual data, these population parameters are replaced by their corresponding sample parameters, that is σ_x is replaced by S_X, σ_y by S_y, ρ_{xy} by r_{XY}, μ_x by $\bar{x}$, and μ_y by $\bar{y}$.

Now the probability that a randomly selected point (X,Y) falls in the region S of the x,y plane is

$$P(S) = \iint_S f(x,y)\,dx\,dy, \tag{4}$$

(Burington and May, 1953). However, the locus of $G = c^2$, where c is a constant, defines an equi-probability ellipse, where for each value of c, f(x,y) is a constant. For example, when $c = 1.1774$, $P = .50$. In general the ellipse defined by a particular value of c is given by

$$P = 1 - \exp(-c^2/2) \tag{5}$$

The lengths of the major and minor axes for each probability value computed are obtained by multiplying the standard deviations along the major and minor axes by the value of c for the particular probability desired.

To obtain the orientation of the elliptical axes, it is necessary to rotate the coordinate axes through an angle ψ so that the cross-product term in (3) disappears. Since this term contains the correlation coefficient ρ_{xy}, the elliptical axes are those along which the x and y components are uncorrelated. The angle of rotation, ψ, is obtained by applying elementary concepts of analytic geometry, where it is shown that, given the general equation of an ellipse centered at the origin of the x-y coordinate system,

$$Ax^2 + Bxy + Cy^2 + F = 0 \tag{6}$$

a rotated set of coordinate axes is made to coincide with those of the ellipse by rotating them through an angle defined by

$$\mathrm{Tan}2\psi = \frac{B}{A - C} \tag{7}$$

In terms of equation (3), this expression becomes

$$\mathrm{Tan}2\psi = \frac{2\rho_{xy}\,\sigma_x\,\sigma_y}{\sigma_x^2 - \sigma_y^2} \tag{8}$$

The variances along the rotated axes are computed from the determinental equation (Hald, 1952)

$$\begin{vmatrix} S_X^2 - K & r_{XY}S_XS_Y \\ r_{XY}S_XS_Y & S_Y^2 - K \end{vmatrix} = 0 \tag{9}$$

Solving for K, one obtains

$$K = \frac{S_x^2 + S_y^2 \pm \sqrt{(S_x^2 + S_y^2)^2 - 4S_x^2S_y^2(1 - r_{xy}^2)}}{2} \tag{10}$$

The larger value for K, K_a, is the variance along the major axis, and the smaller value, K_b, is the variance along the minor axis of the ellipse. The length of these axes is then computed by multiplying $\sqrt{K_a}$ and $\sqrt{K_b}$, the standard deviations along the ellipse axes by the appropriate value of c obtained from equation (5). For example, the .50 contour of the ellipse shown in figure A (Appendix) was computed from the following parameters:

$$\bar{x} = 18.3\text{N}$$

$$\bar{y} = 60.8\text{W}$$

$$S_X = 3.10 \text{ degrees of latitude}$$

$$S_Y = 3.04 \text{ degrees of latitude}$$

$$r_{XY} = .09$$

From equation (8), $\psi = +39.1$ degrees. Computing the length of the axes for the .50 contour, $c = 1.1774$, $\sqrt{K_a} = 3.21$, $\sqrt{K_b} = 2.92$. The length of the major axis of the .50 ellipse is then $c\sqrt{K_a} = 1.1774 \times 3.21 = 3.78$ degrees of latitude, and the length of the minor axis is $c\sqrt{K_b} = 1.1774 \times 2.92 = 3.44$ degrees of latitude.

The storm distributions indicated by the computed ellipses were used to determine the probabilities that storms located over particular areas would affect Cape Kennedy at a given time. These probabilities were determined as follows.

It was found that the best resolution of the data could be obtained by dividing the area studied into 2½ degree latitude-longitude boxes. Positions of hurricanes back to the year 1886 as given by Cry et al (1959) have been punched on computer cards at the National Weather Records Center, Asheville, North Carolina. This card deck was brought up to date through the 1966 hurricane season and computer processed to determine the total number of tropical storms or hurricanes that had been in each 2½ degree latitude-longitude box during the eighty-one years of record. These totals, divided into early-season (Type A) storms (May 1 - July 15), mid-season (Type B) storms (July 15 - October 15), and late-season (Type C) storms (September 15 - October 31) are shown respectively in Figures 17, 18 and 19.

Each 2½ degree box, any part of which was contained within a 99 per cent ellipse, was examined to approximate the portion of the ellipse, in terms of probability, that it contained. These values are the percentages of storms within the

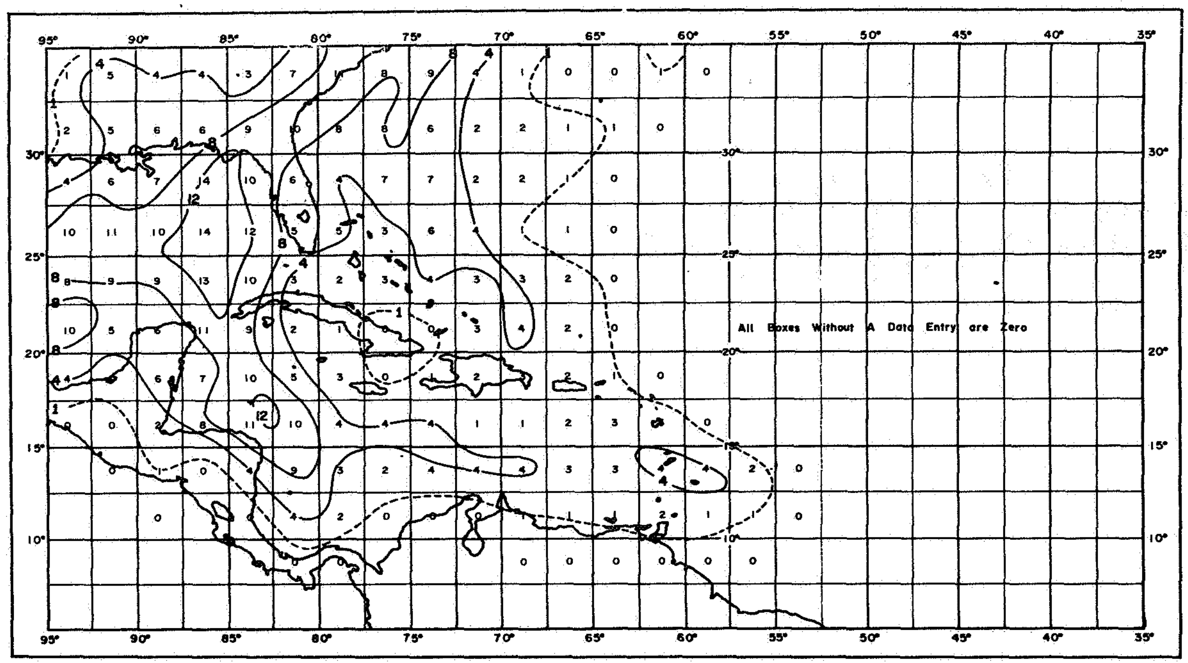


Figure 17: Number of tropical storms or hurricanes passing through each $2\frac{1}{2}$ degree latitude-longitude box 1 May - 15 July 1886-1966.

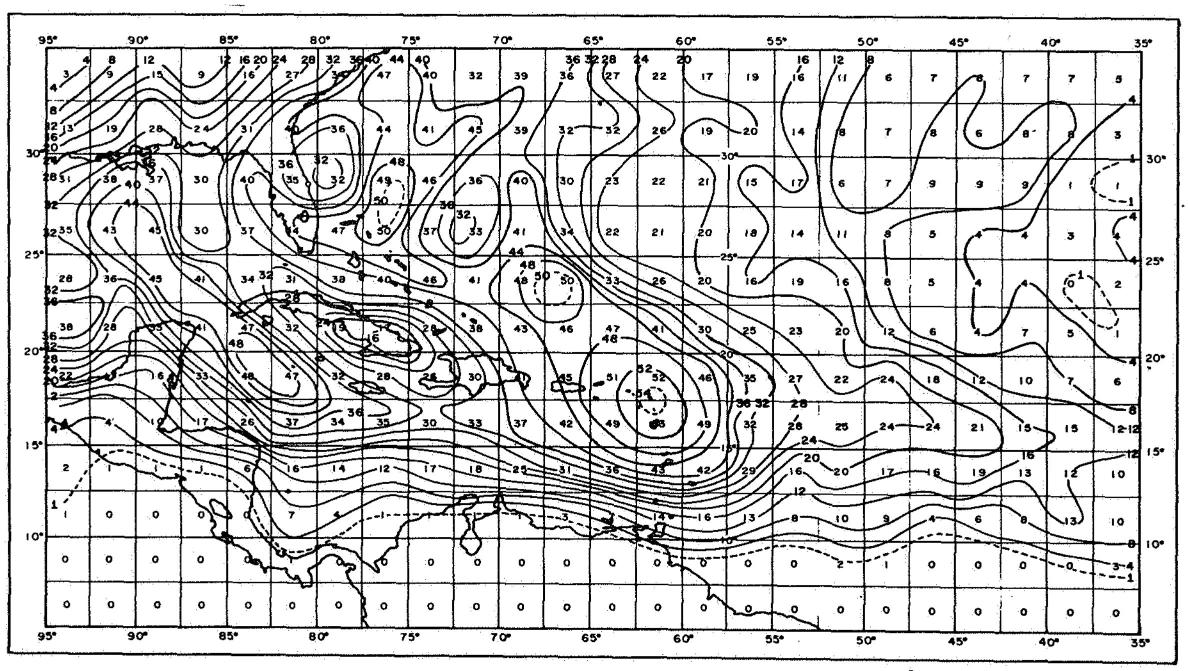


Figure 18: Number of tropical storms or hurricanes passing through each $2\frac{1}{2}$ degree latitude-longitude box 15 July - 15 October 1886-1966.

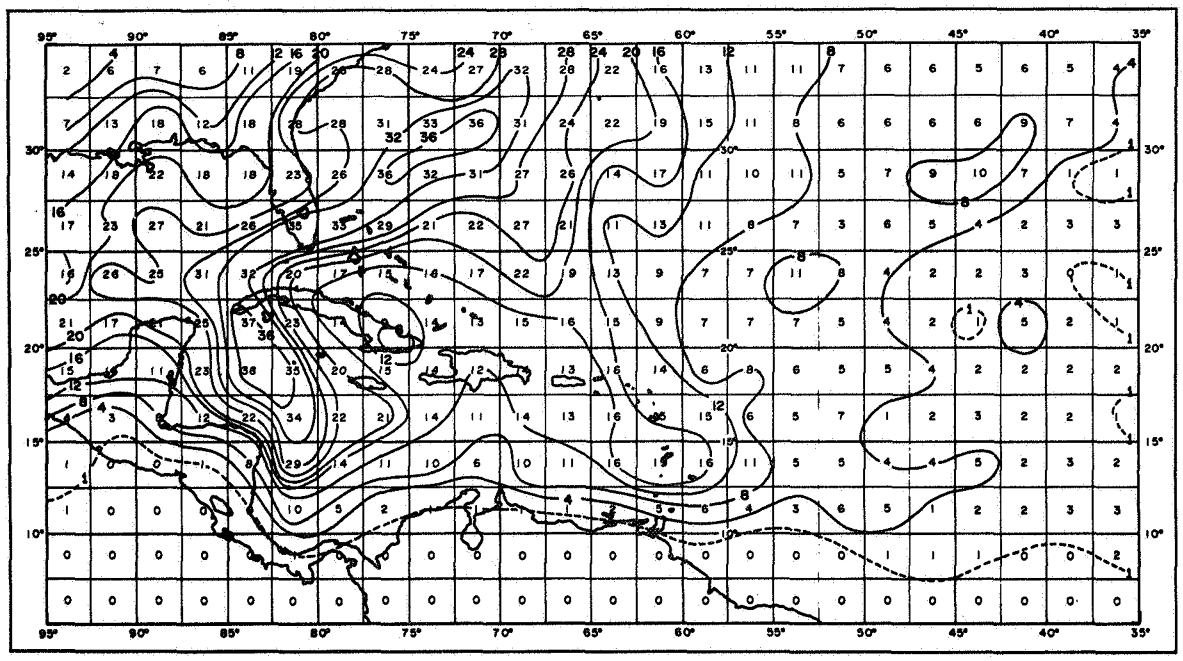


Figure 19: Number of tropical storms or hurricanes passing through each $2\frac{1}{2}$ degree latitude-longitude box 15 September - 31 October 1886-1966.

ellipse that would be located in the included boxes at a particular time prior to their reaching Cape Kennedy. These percentages multiplied by the total number of storms from which the ellipse was computed, yield the number of storms that would have been in the individual boxes, assuming a bivariate normal distribution. This adjusted number of storms affecting Cape Kennedy, divided by the total number of storms in the box during the period of record whether or not these affected Cape Kennedy gives probability of a storm in a given box affecting Cape Kennedy at a specified time.

The results of these computations for the mid- and late-seasons are shown in Figures 20 through 26.

Summarizing the above, the probability of an existing storm in a particular box affecting Cape Kennedy at a given time is given by

$$P' = BN/N_t \qquad BN \leq N_t > 0 \tag{11}$$

where P' = probability that an existing storm will affect Cape Kennedy at a specified time

N = actual number of storms affecting Cape Kennedy from which the ellipse was computed

B = contribution of a box to 99 per cent ellipse

N_t = total number of storms passing through a latitude-longitude box during season over entire period of record.

BN is the theoretical number of storms in each box that should have affected Cape Kennedy. The indicated boundaries on equation (11) must be established because if $N_t = 0$, no storms have passed through the box in question, and if one did appear there, the probability of its affecting any area is indeterminate. Also, BN must be equal to or smaller than N_t to avoid impossible probabilities. In all computations, BN was generally an order of magnitude smaller than N . A sample computation of B is illustrated in the Appendix.

So far, all of the probabilities computed refer only to specific times prior to the onset of critical winds at Cape Kennedy. There remains to determine an estimate of the total probability that an existing storm will affect Cape Kennedy within a specified period of time. The probabilities previously computed, referring to a specific time

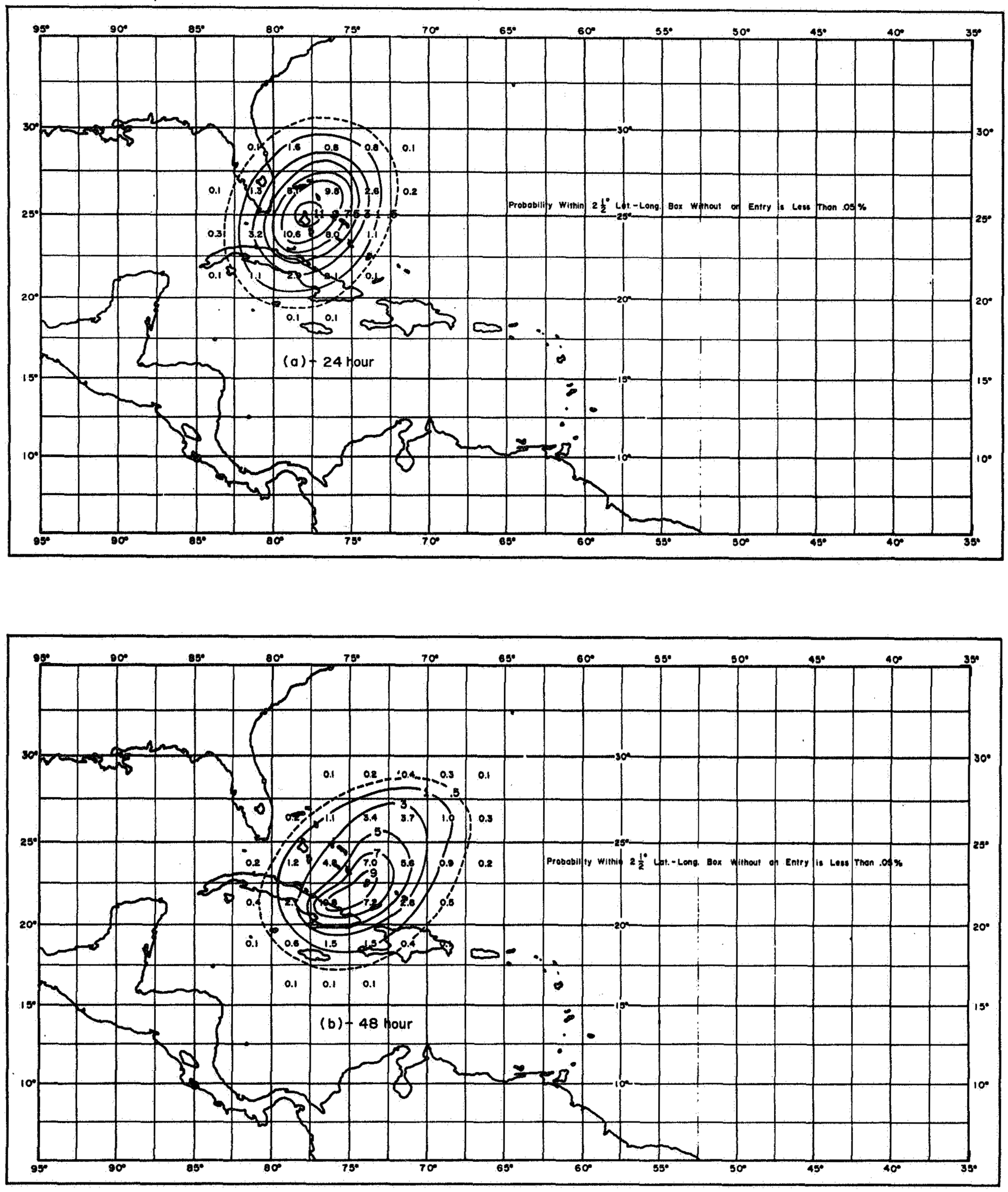


Figure 20: Percent probability that tropical storms or hurricanes, having originated in the Atlantic or eastern Caribbean July 15 - October 15, will produce critical winds at Cape Kennedy at (a) 24 hours, and (b) 48 hours.

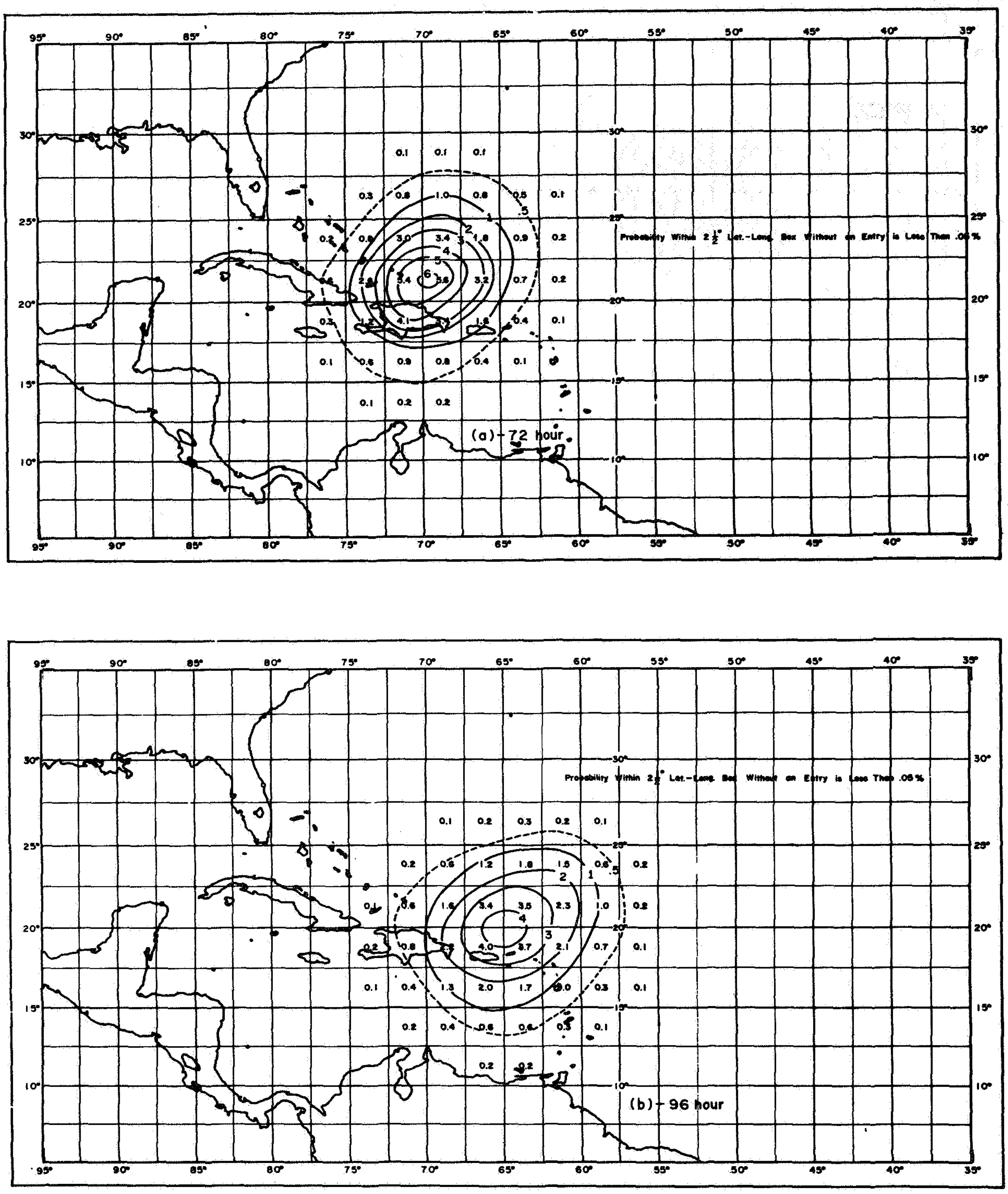


Figure 21: Percent probability that tropical storms or hurricanes, having originated in the Atlantic or eastern Caribbean July 15 - October 15, will produce critical winds at Cape Kennedy at (a) 72 hours, and (b) 96 hours.

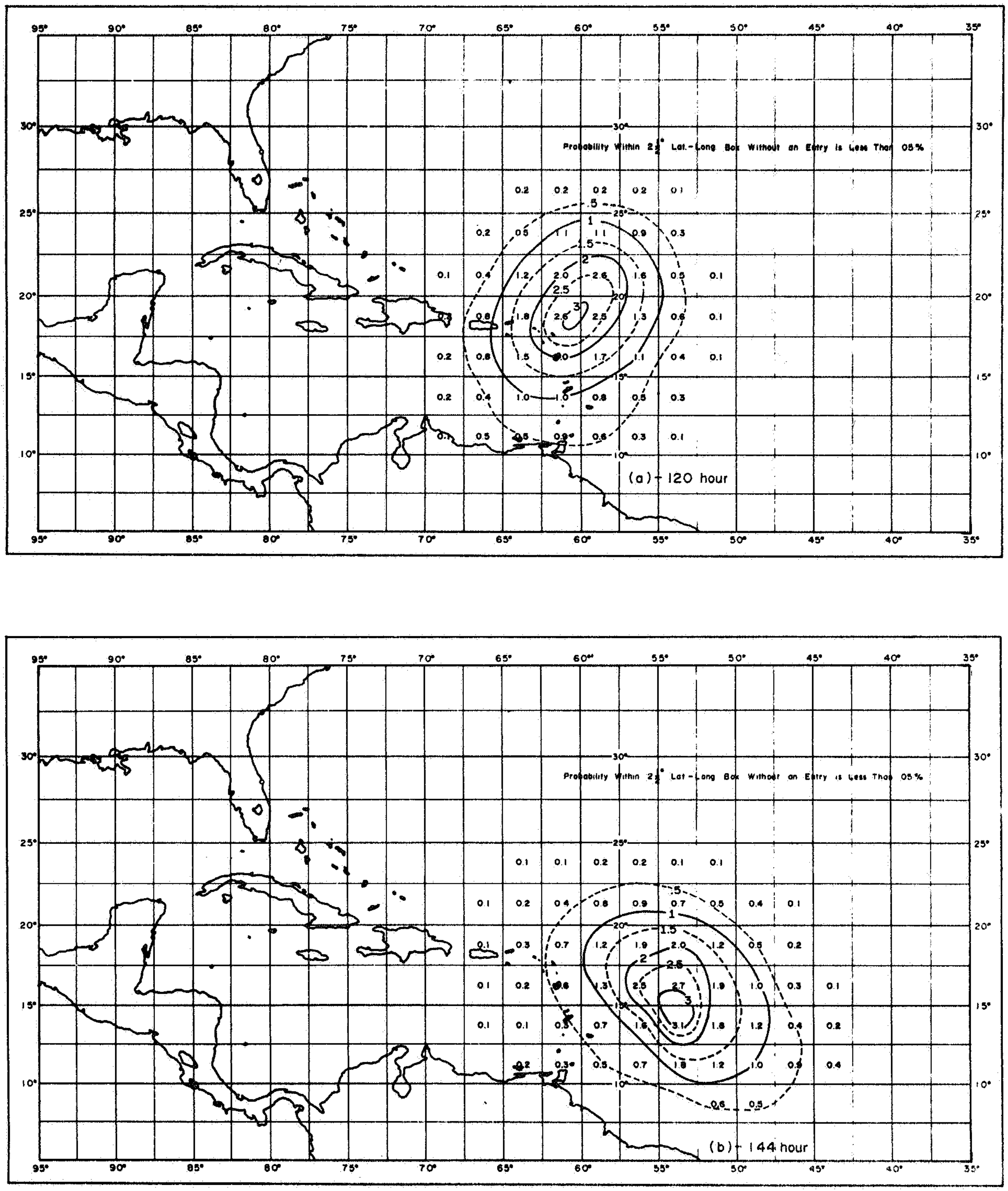


Figure 22: Percent probability that tropical storms or hurricanes having originated in the Atlantic or eastern Caribbean July 15 - October 15 will produce critical winds at Cape Kennedy at (a) 120 hours, and (b) 144 hours.

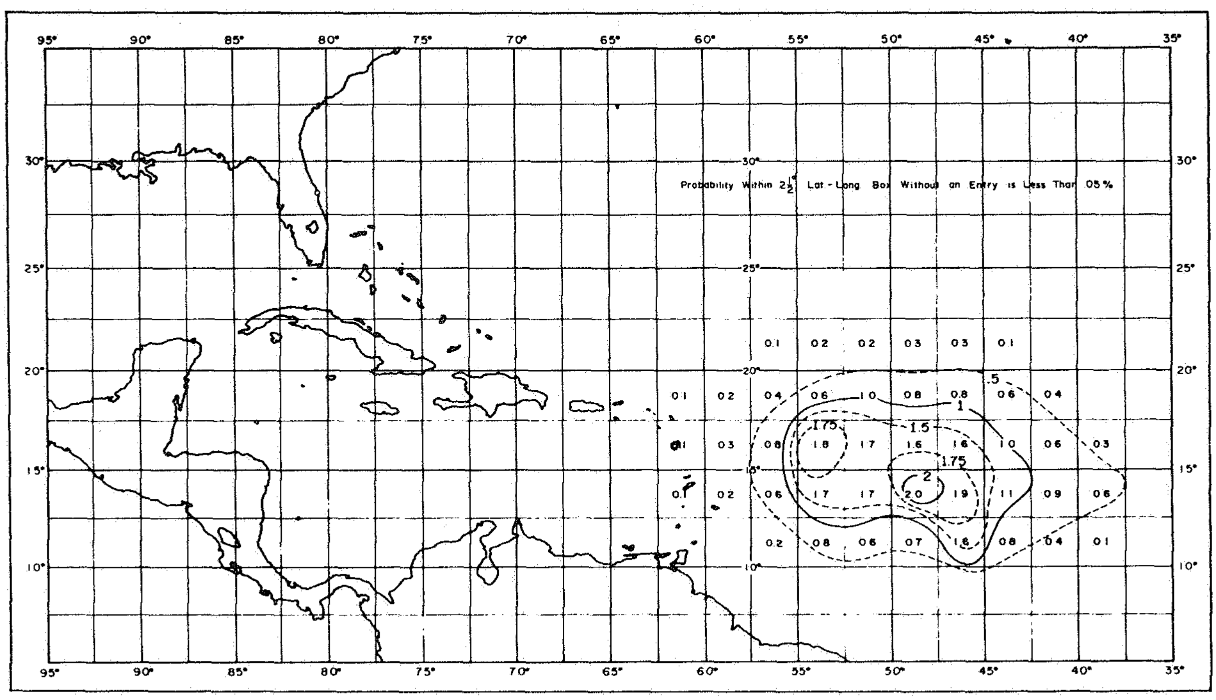


Figure 23: Percent probability that tropical storms or hurricanes having originated in the Atlantic or eastern Caribbean July 15 - October 15 will produce critical winds at Cape Kennedy at the 168th hour.

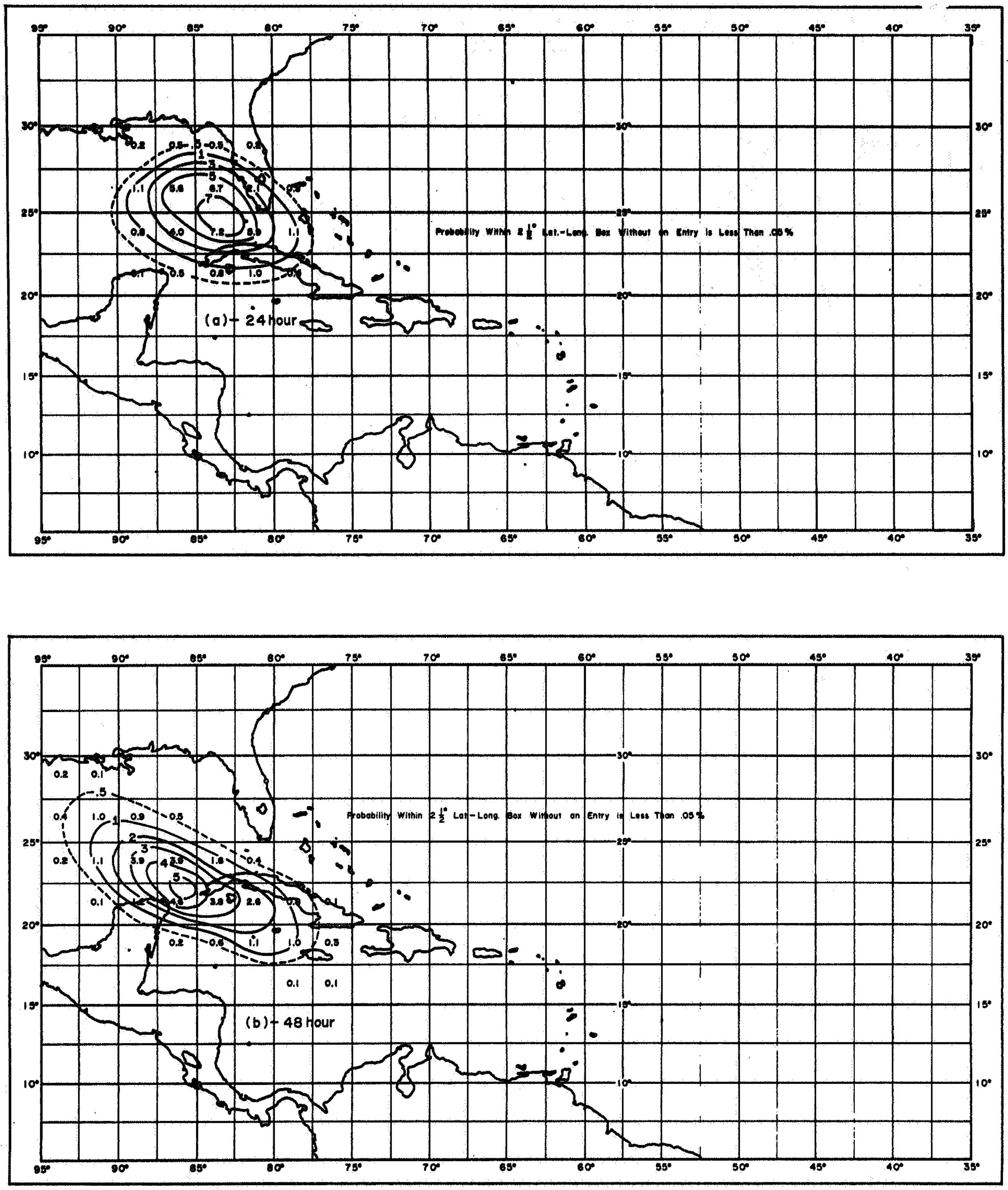


Figure 24: Percent probability that tropical storms or hurricanes, having originated in the western Caribbean or Gulf of Mexico September 15 - October 31, will produce critical winds at Cape Kennedy at (a) 24 hours, and (b) 48 hours.

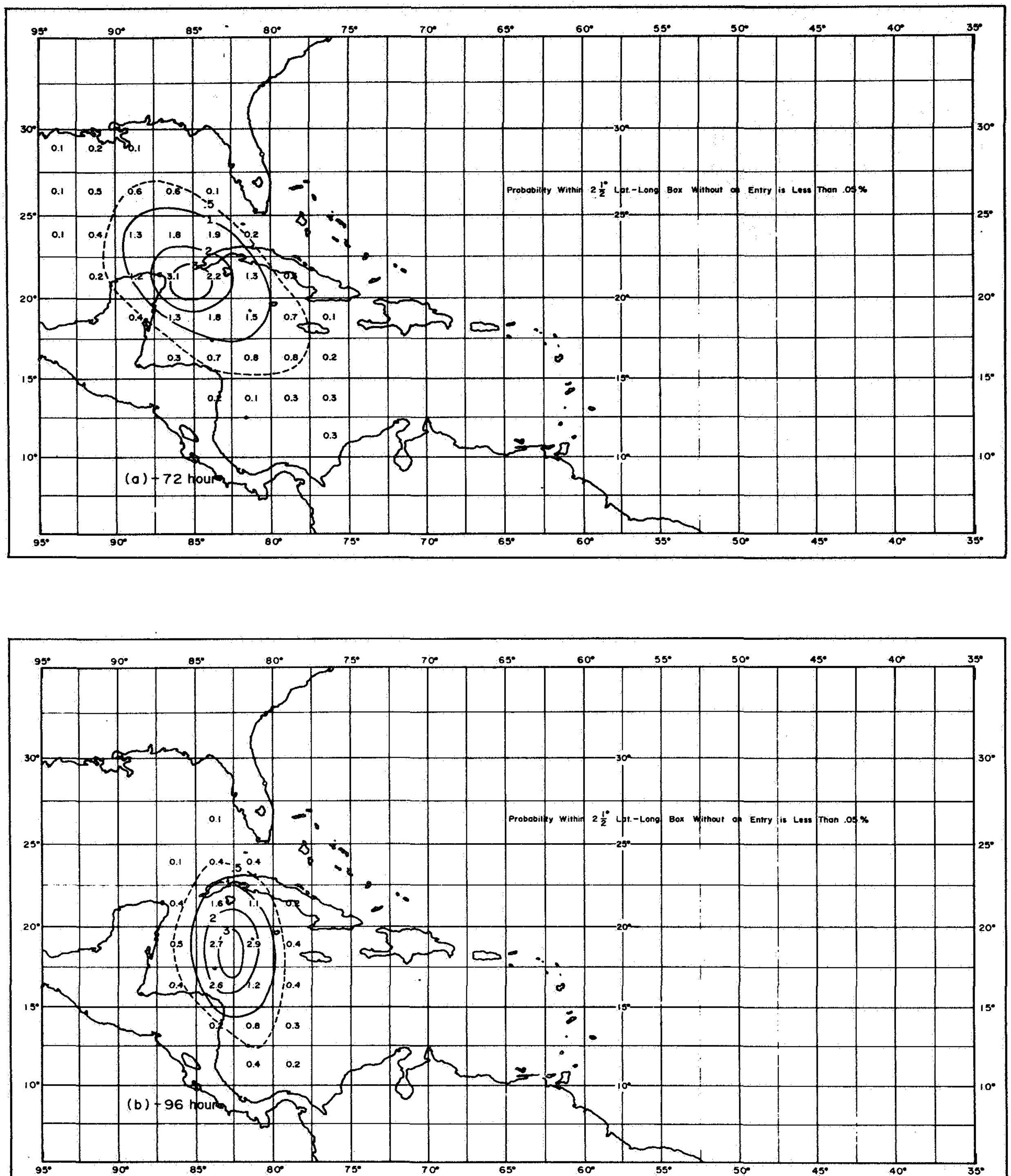


Figure 25: Percent probability that tropical storms or hurricanes, having originated in the western Caribbean or Gulf of Mexico September 15 - October 31, will produce critical winds at Cape Kennedy at (a) 72 hours, and (b) 96 hours.

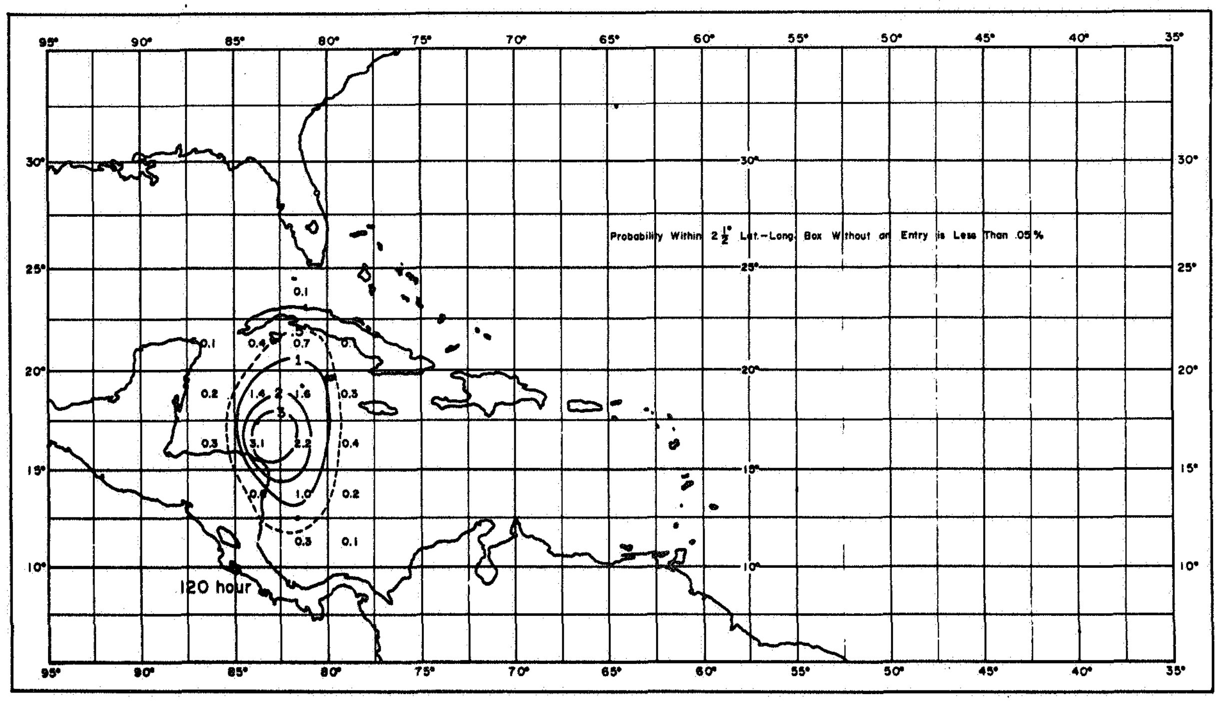


Figure 26: Percent probability that tropical storms or hurricanes, having originated in the western Caribbean or Gulf of Mexico September 15 - October 31 will produce critical winds at Cape Kennedy at the 120th hour.

prior to the onset of critical winds, cannot simply be added to obtain the total probability of Cape Kennedy being affected by an existing storm. In the cumulative process, it is necessary to consider the number of boxes in which the storms affecting Cape Kennedy were located during each 24-hour period. When these are counted and the sum divided by N (the number of storms from which the ellipse was computed), a factor, M, is obtained which can be applied to each box within the ellipse. This has the effect of adding storms to each box, because the number of storms located in each box during a given time span is considered, not merely those storms that were in the box at a specified time. For Atlantic and eastern Caribbean storms, this effectively increased the box count by a factor ranging from 2.5 to 3.3, and for the western Caribbean and Gulf of Mexico storms by a factor ranging from 1.5 to 3.7. The range in the factors reflects the variation in translational speeds of the storms in different areas.

In summary, the total or cumulative probability within a specified period is obtained by adding the sum of probabilities obtained from equation (11) plus a quantity which depends on the number of additional boxes in which a storm affecting Cape Kennedy has been during the 24-hour period under consideration. The latter quantity can be expressed as

$$P' \frac{M \Delta t}{24} - 1 ,$$

where M is the mean number of boxes in which the storms have been during the 24-hour period, Δt is the time in hours between ellipses. Adding this quantity to P' for the ellipse in question and simplifying, one obtains for the 24-hour contribution:

$$P_{24} = P' \frac{M \Delta t}{24} \qquad (12)$$

If the ellipses are spaced at 24-hour intervals (as they are here), this reduces to

$$P_{24} = P'M \qquad (13)$$

The total or cumulative probability within a specified period of time and for a given box is then:

$$P = \sum_{i=0}^{n} P_i M_i \qquad (14)$$

where n is the number of days within which the cumulative probabilities are computed.

For example, suppose the probability of a storm in a given box affecting Cape Kennedy in 120 hours is 2.5%, M is 3.0; the 24-hour contribution from T-120 hours to T-96 hours is $P_{24} = P'M = 2.5 \times 3.0 = 7.5\%$. The sum of all such 24-hour contributions is the total probability given by equation (14).

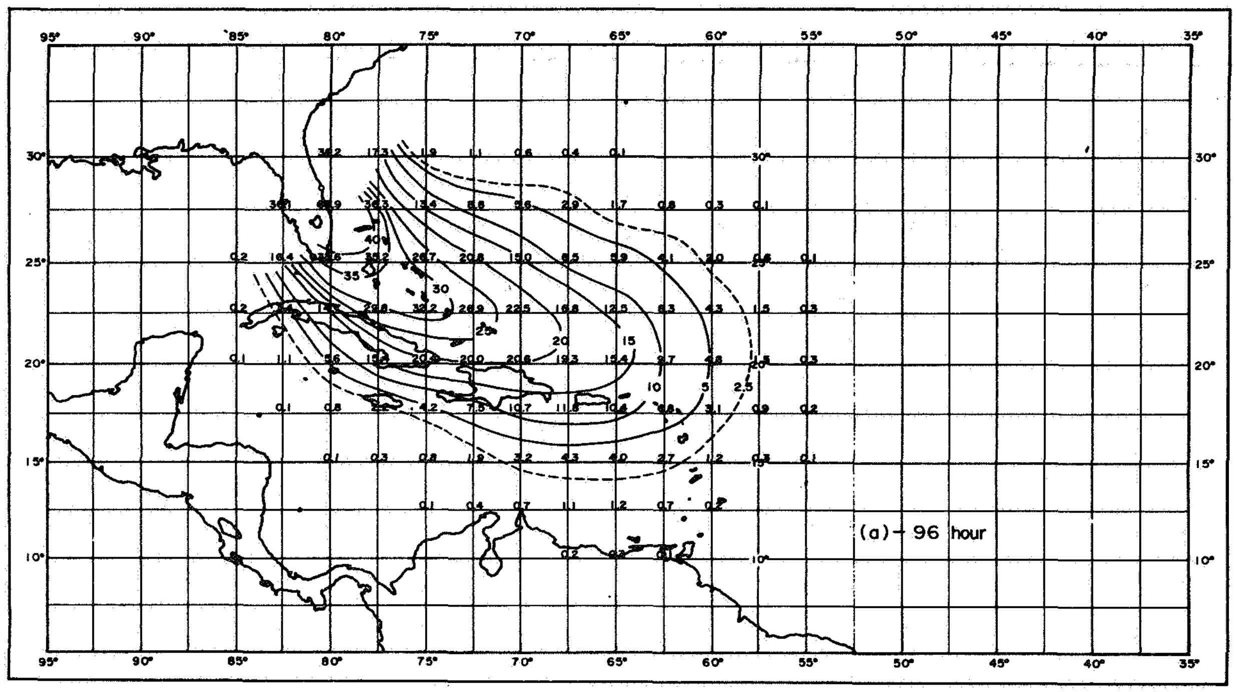
The probabilities of storms producing critical winds at Cape Kennedy within specified periods of time, hereafter referred to as cumulative probabilities, are shown in Figures 27 through 29. The data presented on these charts were smoothed by averaging the numbers in the boxes at their common intersection, boxes with no entry being counted as zero.

A further check was made on the validity of these cumulative probability figures by computing the actual frequency within 168 hours with which storms passing through the Atlantic affected Cape Kennedy with critical winds during the mid-season period July 15 - October 15. This was done simply by computing the ratio of the number of storms passing through each box that affected Cape Kennedy to the total number of storms passing through each box. These frequencies are shown in Figure 30. Note that the frequencies are similar to the probabilities computed from the ellipses (Figure 28b) except in the eastern Atlantic where the total number of storms that eventually produced critical winds at Cape Kennedy was very small, and a smooth pattern could not be obtained in the analysis. A check on the western Caribbean and Gulf of Mexico storms showed that results obtained from computations using the ellipses were similar also to the actual frequencies, although of course a much smoother pattern was obtained from the data computed from the ellipses.

PROBLEM 3

The third and final problem was to determine the probability of an existing tropical cyclone producing critical winds at Cape Kennedy considering the storm's antecedent motion.

Figures 27 and 28 presented data on the probability of an existing Atlantic or eastern Caribbean tropical cyclone producing critical winds at Cape Kennedy without regard to the storm's direction of motion. For example, Figure 28b indicates that a tropical cyclone located at 20°N, 65°W has a 19% chance of producing critical winds at Cape Kennedy



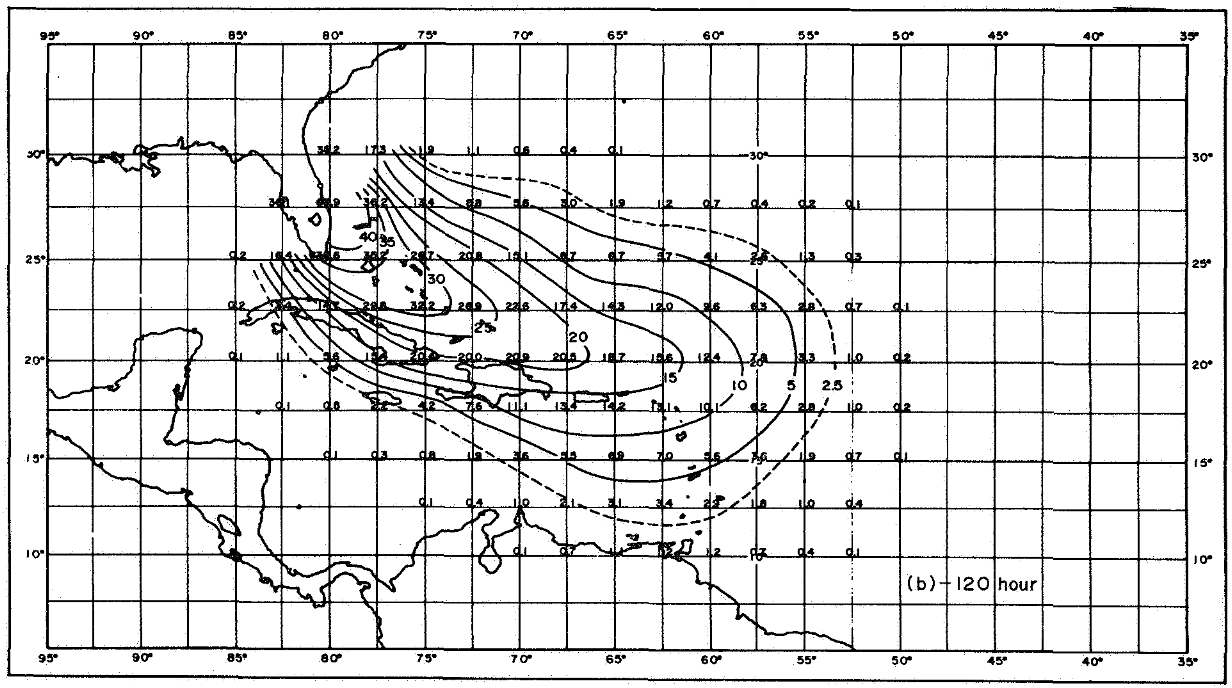


Figure 27: Cumulative percent probability of a tropical storm or hurricane, located at a given point and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within (a) 96 hours, and (b) 120 hours.

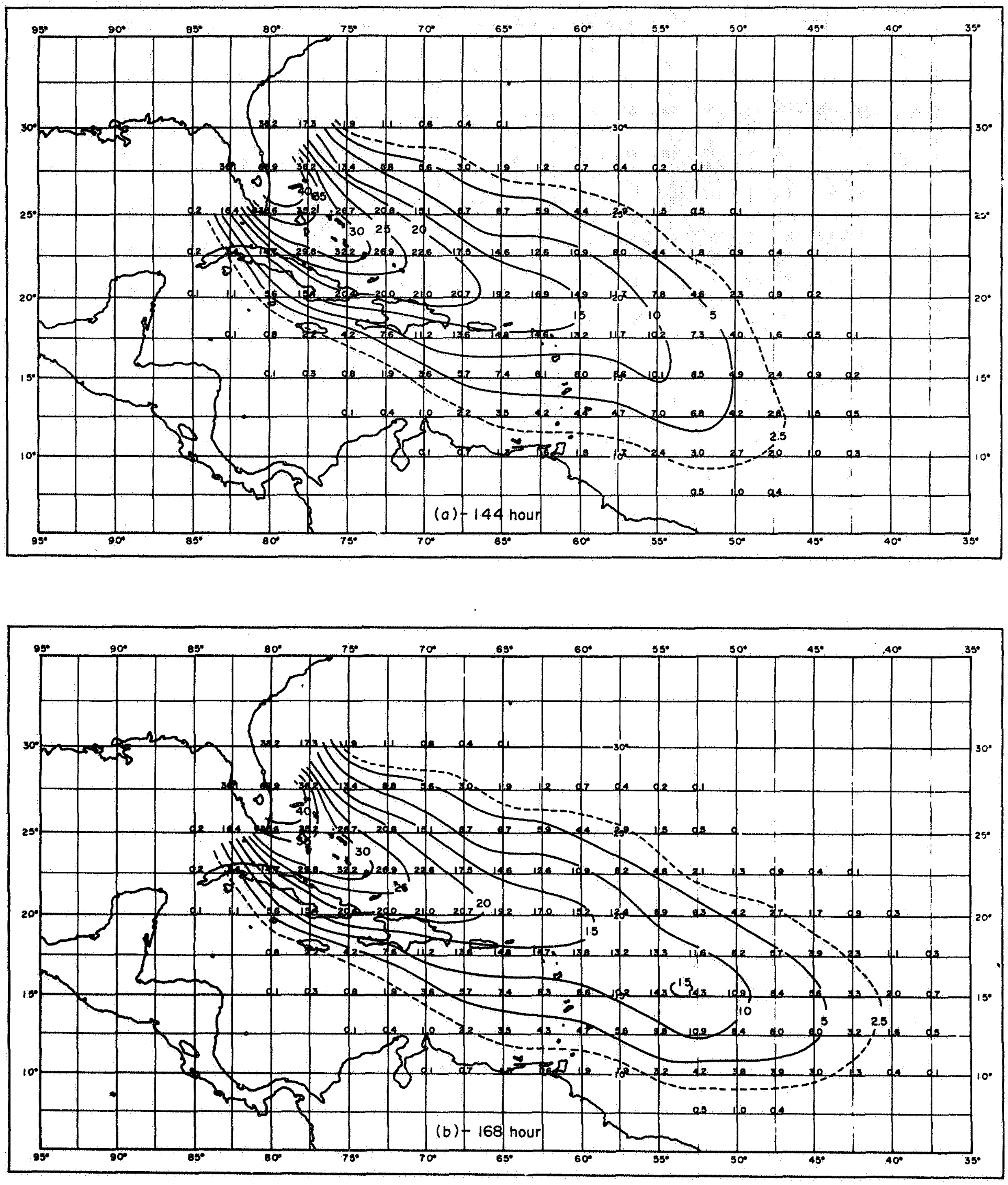
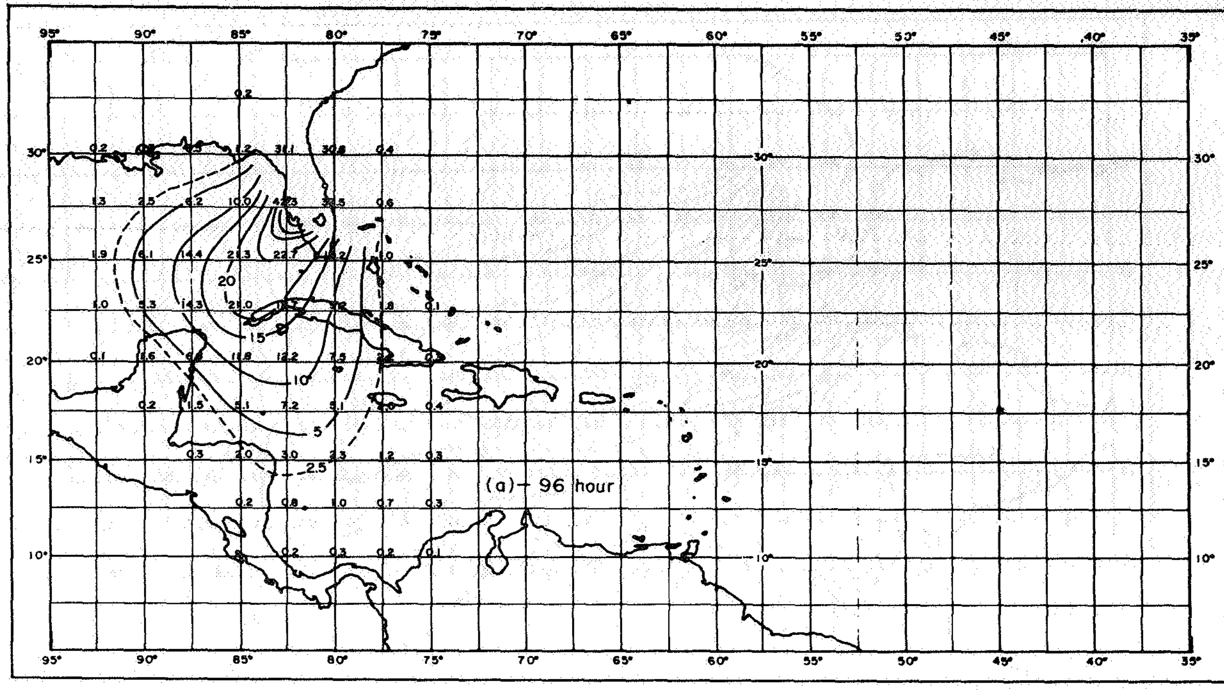


Figure 28: Cumulative percent probability of a tropical storm or hurricane located at a given point and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within (a) 144 hours, and (b) 168 hours.



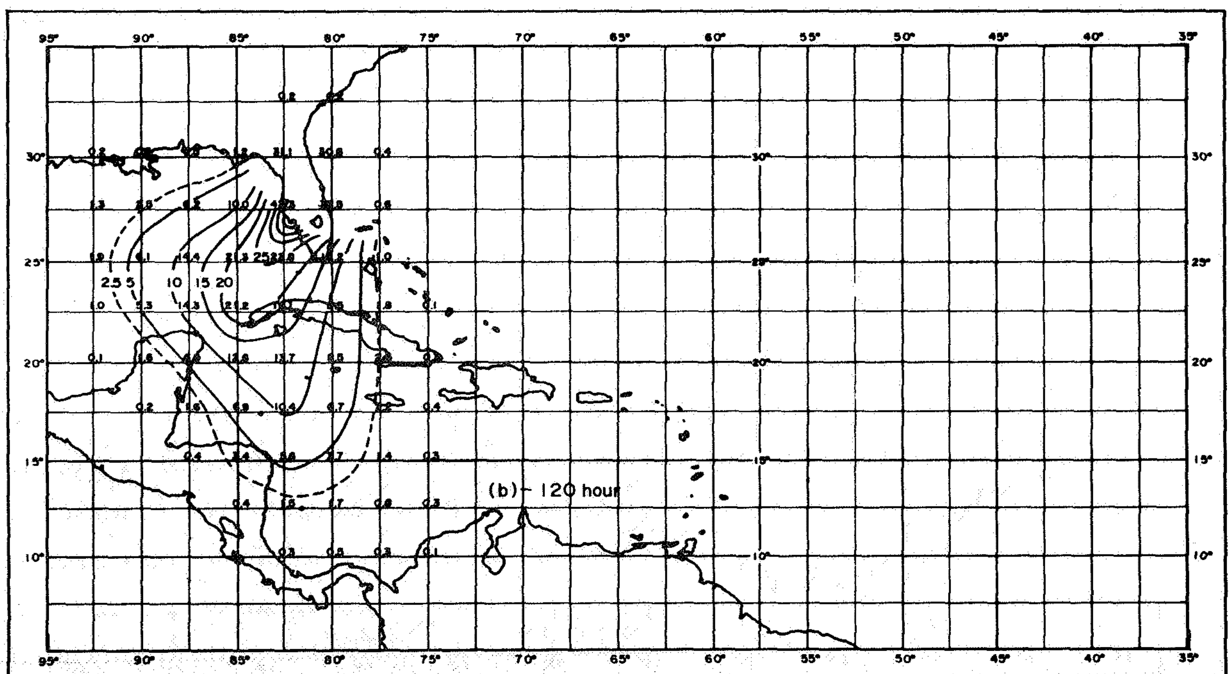


Figure 29: Cumulative percent probability of a tropical storm or hurricane, located at a given point and having originated in the western Caribbean or the Gulf of Mexico September 15 - October 31, producing critical winds at Cape Kennedy within (a) 96 hours, and (b) 120 hours.

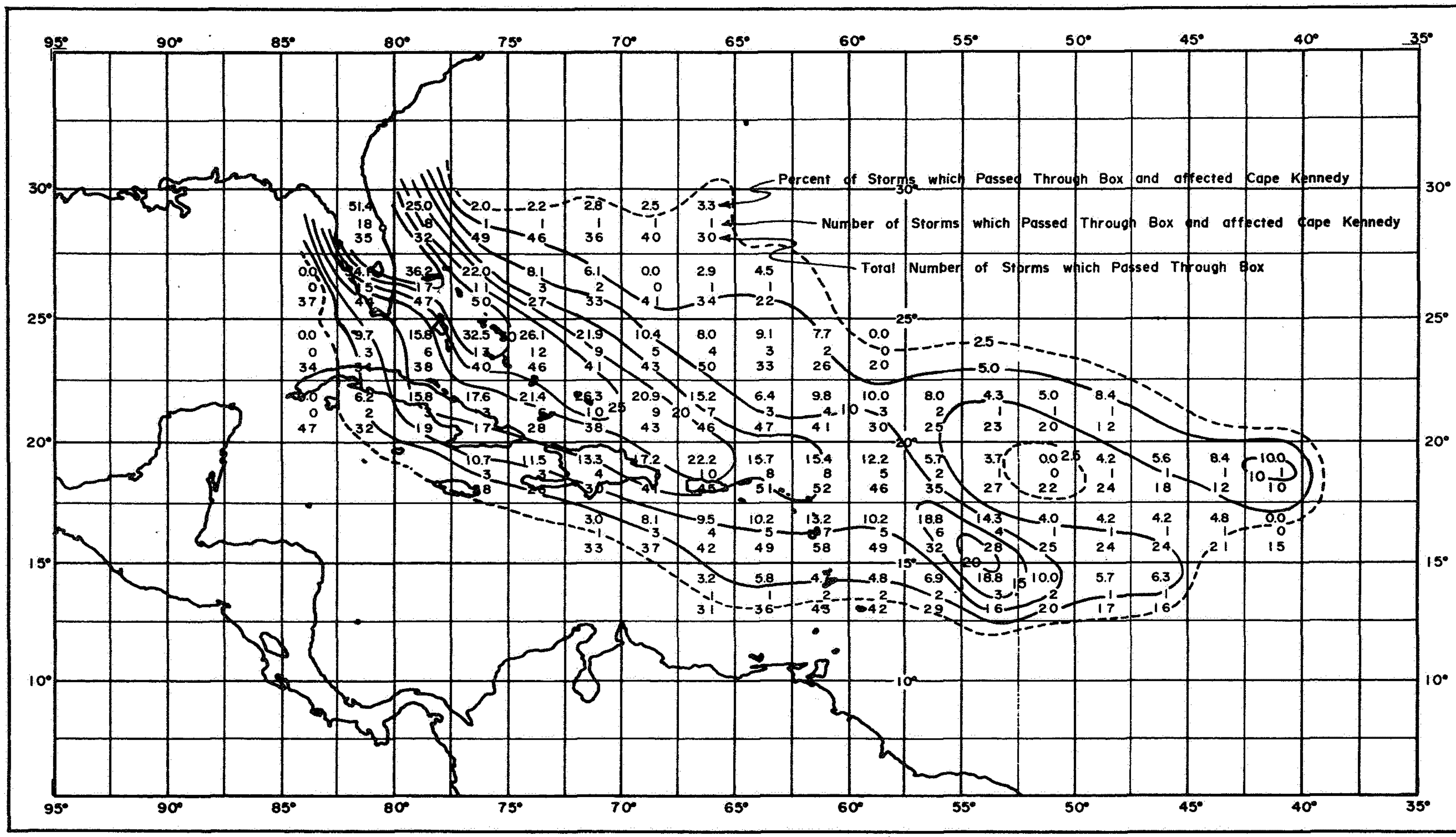


Figure 30: Observed frequency of tropical storms or hurricanes, located in a given $2\frac{1}{2}$ degree latitude-longitude box in the eastern Caribbean or the Atlantic July 15 - October 15, 1886-1966, which produced critical winds at Cape Kennedy within 168 hours.

within 168 hours. It is apparent, however, that if a storm is located at this given point and is moving in some direction away from Cape Kennedy, say towards the northeast, the probability would be considerably less than 19%. On the other hand, a storm located at this same site moving toward the WNW or NW would have a higher probability than 19% of producing critical winds at Cape Kennedy. It is desirable, therefore, to stratify further the data of Figures 27 and 28 in such a manner that the final cumulative probabilities are dependent on the storm's direction of motion.

A computer program was written to count the number of storms passing through each $2\frac{1}{2}$ degree latitude-longitude box from each of the eight directions measured clockwise from north (north through northeast, northeast through east, etc.). Storm motion was taken as the motion of the storm upon its entry into a given box. The program was run initially for all storms of a given category, regardless of their effect on Cape Kennedy. The program was then run for a second time including only those storms which eventually yielded critical winds for Cape Kennedy.

The data pertaining to the latter category of storms were processed further to determine the variation of storm movement with longitude. Table 2 shows the results of this processing and clearly demonstrates that for longitudes east of 77.5°W, nearly all of the storms which affected Cape Kennedy were moving in a direction from east through southeast but with a few cases from the adjacent directions of east through northeast or southeast through south. Given a larger data sample, it is considered likely that each of the zones would observe at least a few cases in the adjacent boxes. It appears, therefore, that insofar as longitudes east of 77.5°W are concerned, the average direction of movement of storms which eventually bring critical winds to Cape Kennedy is, for all practical purposes, constant. It was permissible, therefore, and in fact desirable, to combine the longitude zones east of 77.5°W into a single zone. This averaging process has the effect of partially compensating for the limited data sample under consideration. Referring again to Table 2, the two zones west of 77.5°W were retained as separate entities since the directional values within these two latter zones show distinctly the trend for recurvature in these longitudes. The modifications just described are shown in Table 3.

Table 2: Direction of motion of Type B storms within specified longitude zones prior to producing critical winds at Cape Kennedy

Number of Cases Observed within Long. Zones (°W)	N-NE	NE-E	E-SE	SE-S	S-SW	SW-W	W-NW	NW-N
80.0 to 82.5			11	8	5			
77.5 to 80.0			24	7	1			
75.0 to 77.5			31					
72.5 to 75.0			28					
70.0 to 72.5			25	2				
67.5 to 70.0			25					
65.0 to 67.5			28					
62.5 to 65.0			21					
60.0 to 62.5			22	2				
57.5 to 60.0		1	15	1				
55.0 to 57.5		1	11	1				
52.5 to 55.0			8					
50.0 to 52.5			5					
47.5 to 50.0			6					
45.0 to 47.5			2					
42.5 to 45.0			1					
40.0 to 42.5			1					

Table 3: Direction of motion of Type B storms within specified combined longitude zones prior to producing critical winds at Cape Kennedy

Movement from	Longitude Zones (°W)					
	80.0 - 82.5		77.5 - 80.0		East of 77.5	
	Cases	% of total	Cases	% of total	Cases	% of total
N thru NE	0	0.0	0	0.0	0	0.0
NE thru E	0	0.0	0	0.0	2	0.9
E thru SE	11	45.8	24	74.3	229	96.6
SE thru S	8	33.3	7	22.6	6	2.5
S thru SW	5	20.9	1	3.1	0	0.0
SW thru W	0	0.0	0	0.0	0	0.0
W thru NW	0	0.0	0	0.0	0	0.0
NW thru N	0	0.0	0	0.0	0	0.0
Total cases	24	100.0	32	100.0	237	100.0

The data from Table 3 provide sufficient additional information to subdivide the cumulative non-directional probabilities obtained from Figures 27 and 28 into cumulative directional probabilities. The percentages listed in Table 3 can be considered directional weighting factors. Designating these factors as F_d, their summation over all eight directions of movement plus no movement is

$$\sum_{i=1}^{9} F_{di} = 1 .$$

For a given $2\frac{1}{2}$ degree latitude-longitude box and for a given cumulative time period, the necessary computations can be expressed as follows:

$$P_d = \frac{P \ N_t \ F_d}{N_d} \qquad PN_tF_d \leq N_d > 0 \tag{15}$$

where:

P_d = cumulative probability of a tropical cyclone moving from direction d producing critical winds at Cape Kennedy

P = cumulative probability of a storm producing critical winds at Cape Kennedy without regard to the storm movement

N_t = total number of storms passing through the given $2\frac{1}{2}$ degree latitude-longitude box

F_d = appropriate directional weighting factor $\sum_{i=1}^{9} F_{di} = 1$ from Table 3

N_d = actual count of total number of storms passing through the given $2\frac{1}{2}$ degree latitude-longitude box from a direction d.

As in equation (11), equation (15) must be bounded to rule out the impossible situations. Once again, however, these boundaries were not approached in actual computations.

In formula (15), the product PN_t in the numerator equals the number of storms in a given box calculated to have affected Cape Kennedy. This product multiplied by the weighting factor (F_d) yields the number of storms moving from a particular direction which eventually reached Cape Kennedy. Dividing the numerator by N_d gives the desired directional probability. The weighted sum of the directional probabilities equals the non-directional probability at each point. That is,

$$\sum_{i=1}^{9} P_{di} F_{di} = P,$$

where the summation is again over all directions of movement considered, including no movement.

As an example of the computation of a specific cumulative directional probability, suppose it is desired to determine the probability of a storm located in the center of the 2½ degree latitude-longitude box located just south of 20°N and just west of 60°W of producing critical winds at Cape Kennedy within 168 hours. The storm is moving from the ESE. In formula (15),

$$P = .16 \text{ (from Figure 28b)}$$

$$N_t = 52 \text{ (from Figure 18)}$$

$$F_d = .966 \text{ (from Table 3)}$$

$$N_d = 46 \text{ (from computer output, these figures not included in report)}$$

$$P_{ese} = \frac{.16 \times 52 \times .966}{46} = .175 \text{ or } 17.5\%$$

Thus, the fact that the storm is moving towards Cape Kennedy increases the probability of this storm producing critical winds at Cape Kennedy from 16% to 17.5%.

A computer program was written to perform the necessary computations for Type B storms for each of the eight directions and for each of the cumulative time periods (168 hours, 144 hours, 120 hours, and 96 hours) and to smooth the data over four adjacent boxes. The results of these computations along with an isoline analysis of the plotted data are shown in Figures 31 through 43.

The computer program was also run for the Type C (Caribbean and Gulf of Mexico) storms. However, because of the small data sample, the results were, for the most part, inconclusive, and are not included in this report.

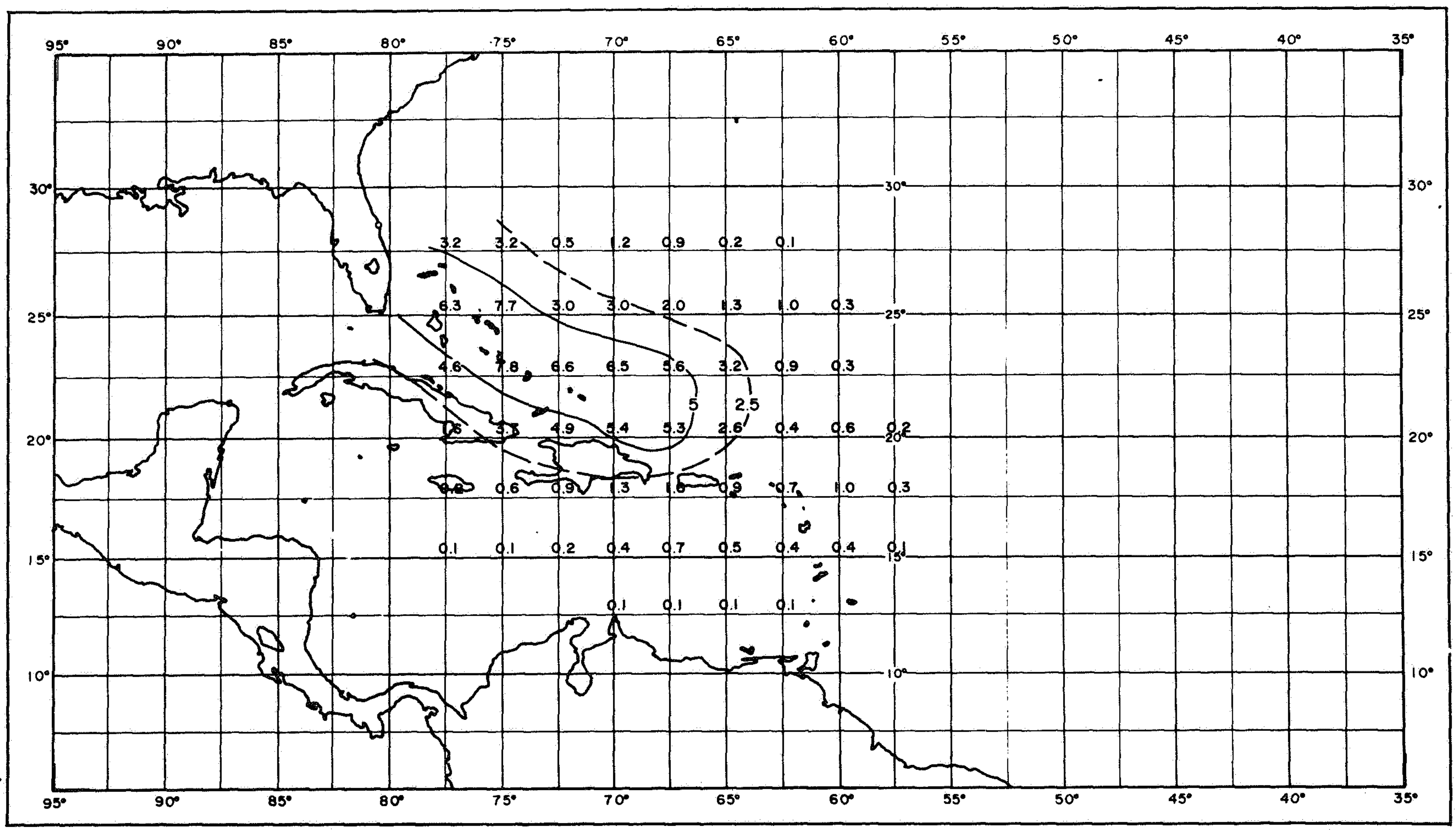


Figure 31: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through northeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 96 hours.

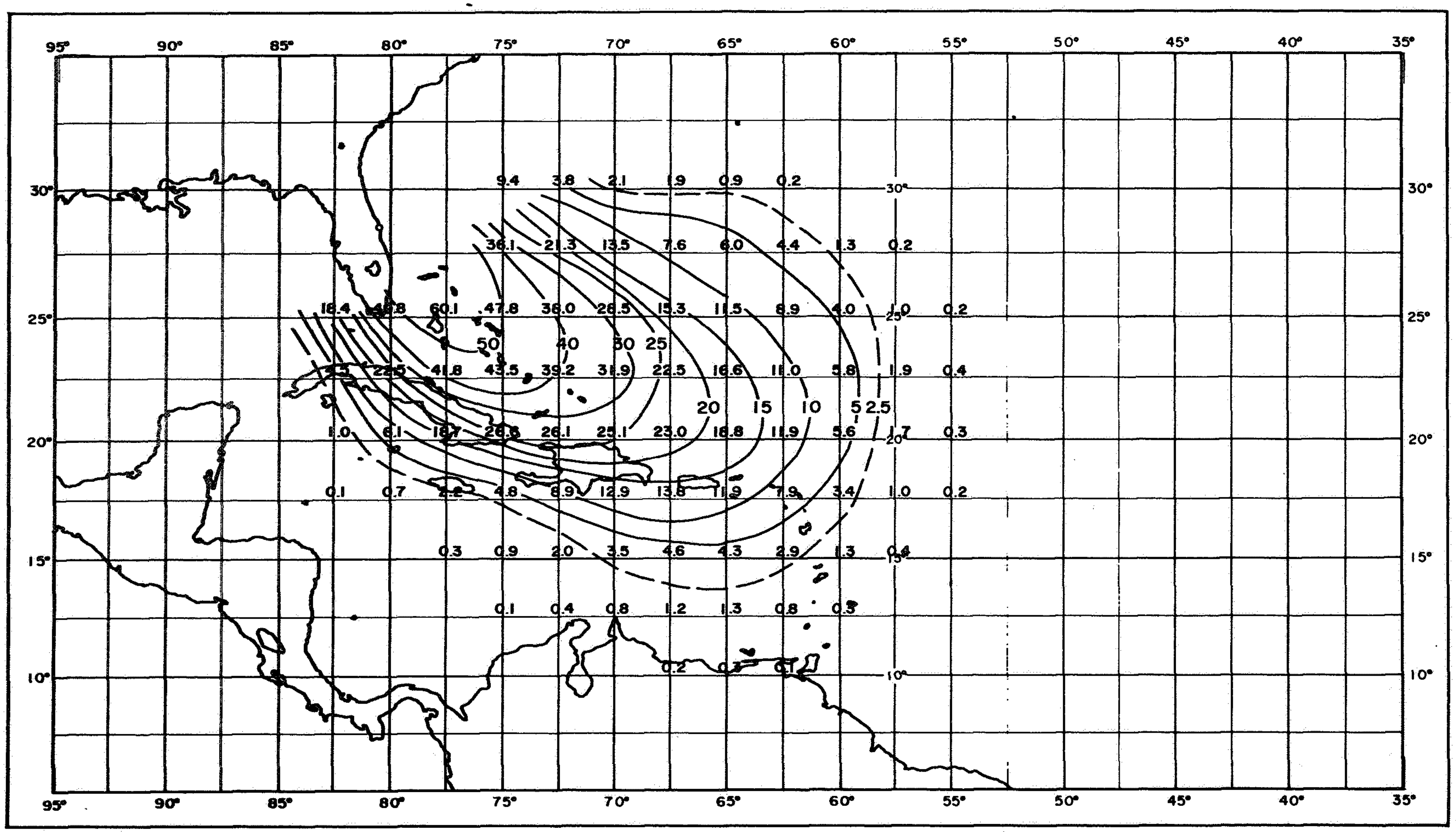


Figure 32: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through southeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 96 hours.

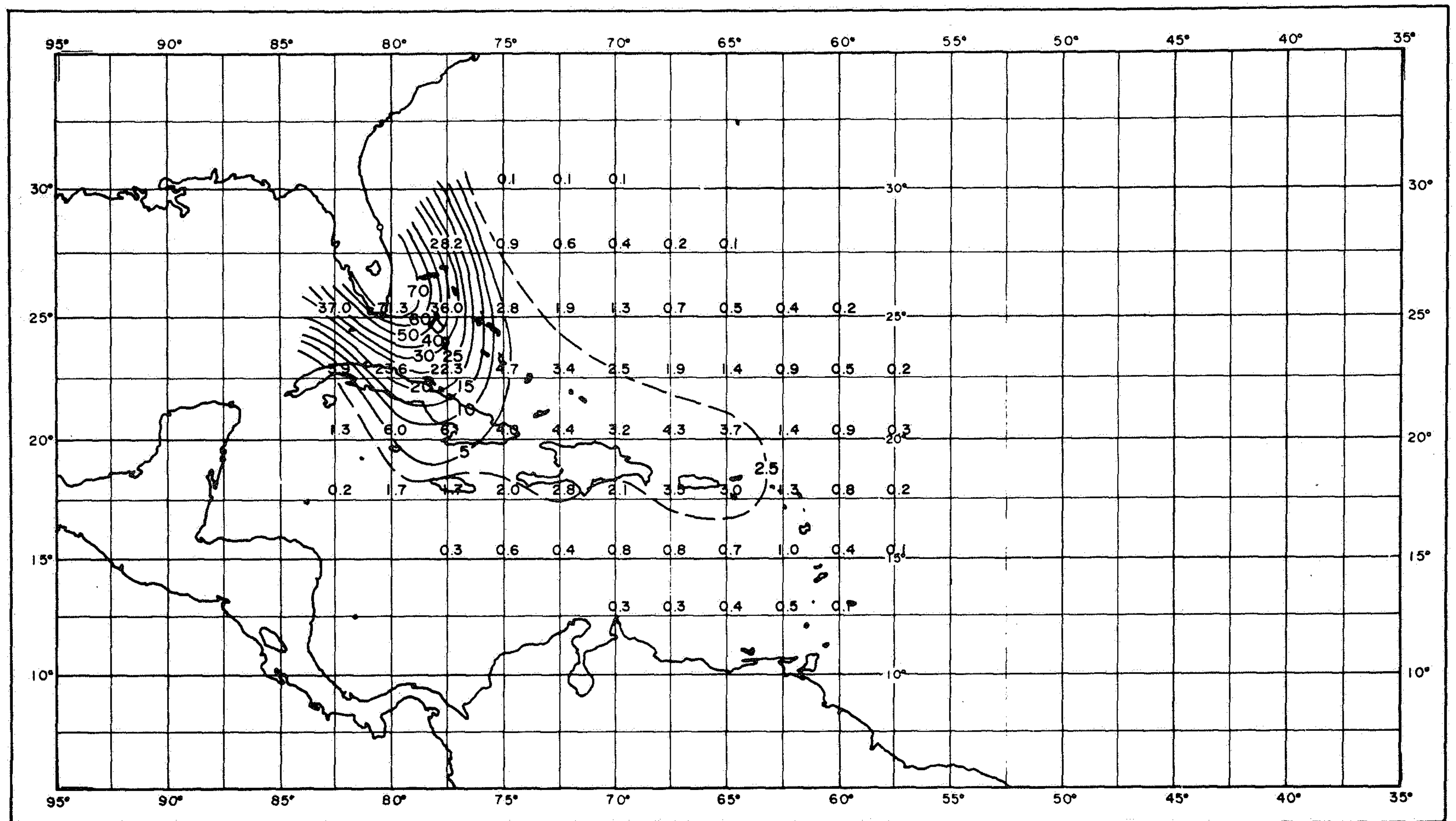


Figure 33: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the southeast through south and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 96 hours.

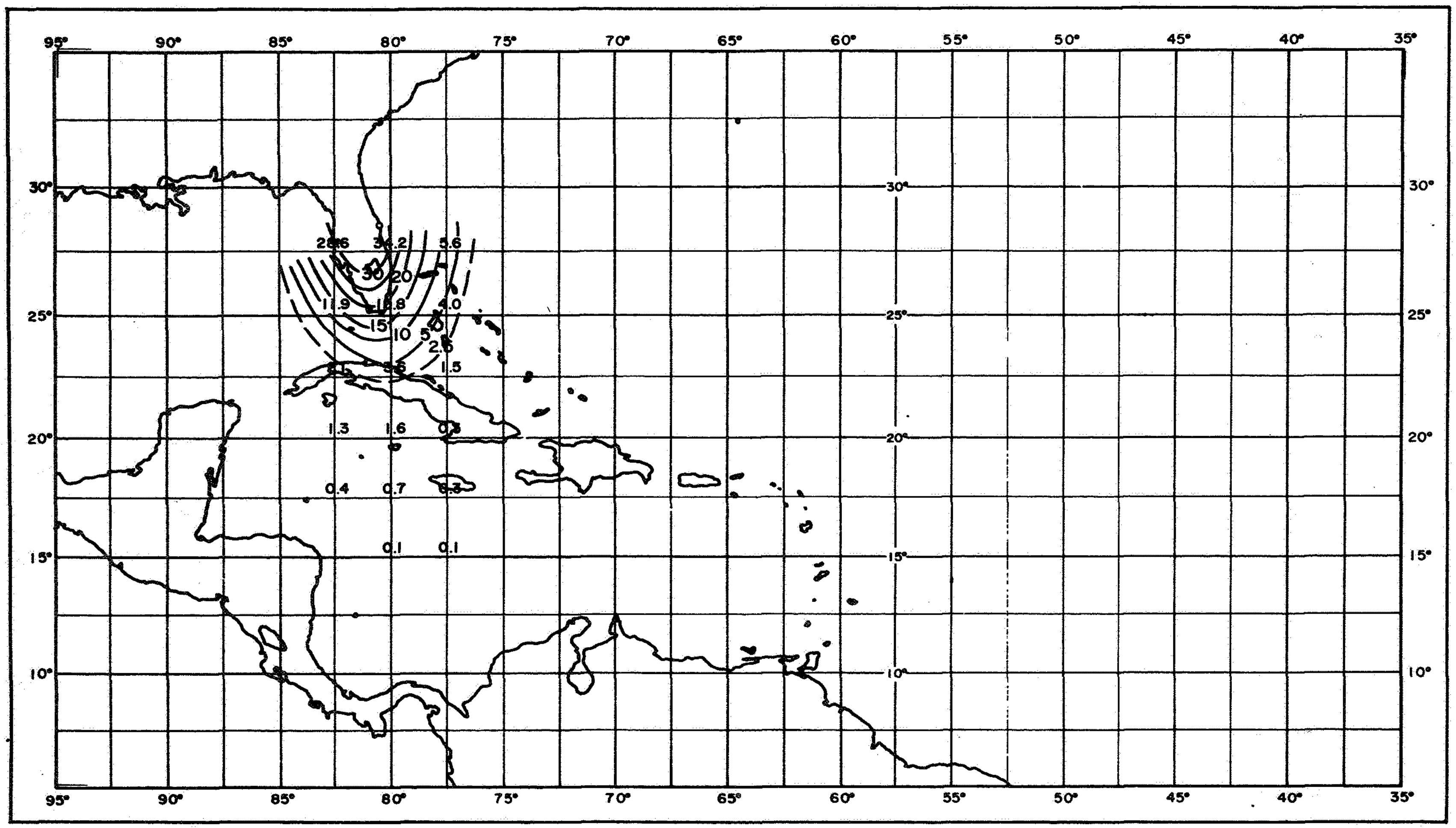


Figure 34: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the south through southwest and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 96 hours, or 120 hours, or 144 hours, or 168 hours.

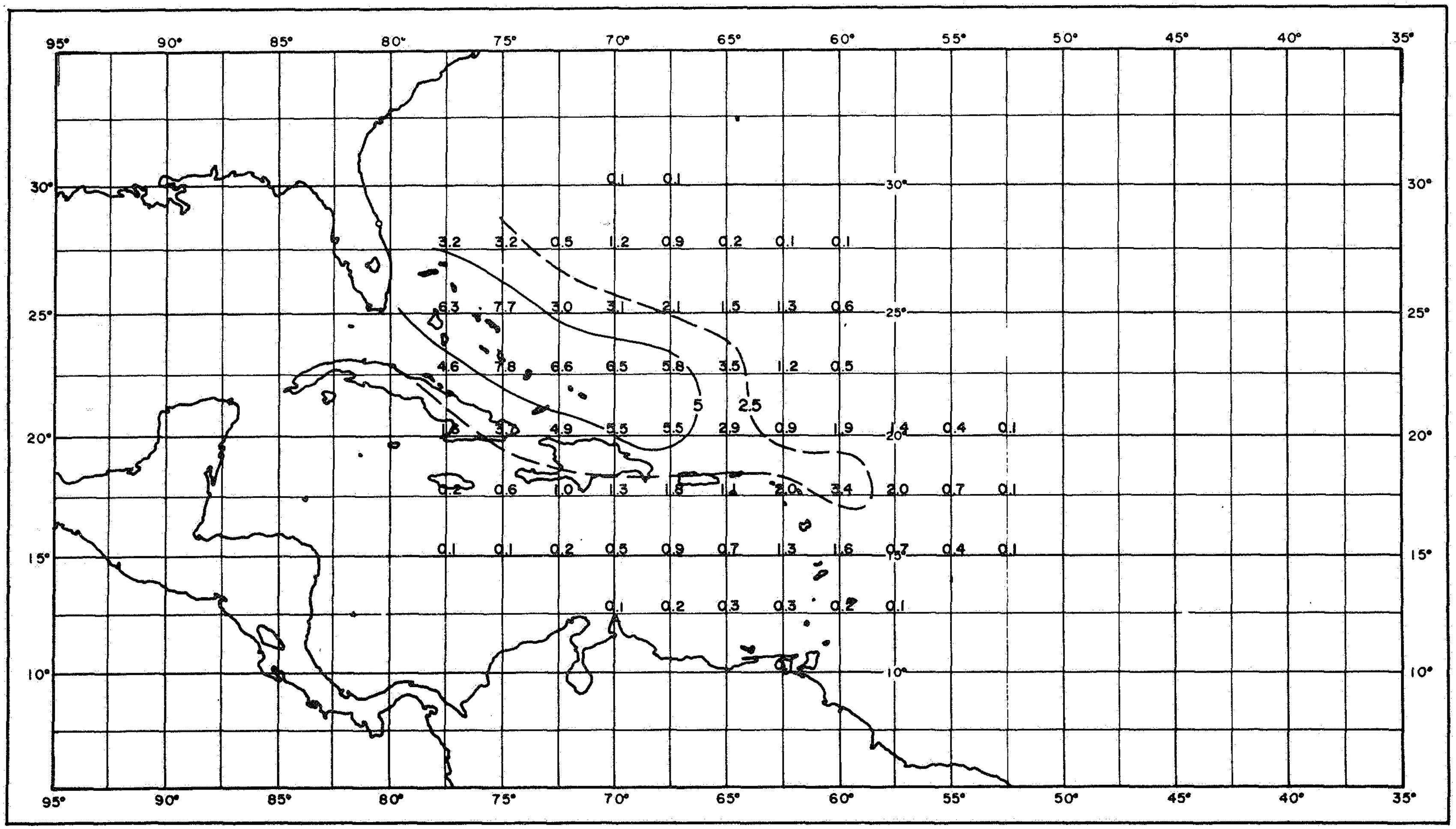


Figure 35: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through northeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 120 hours.

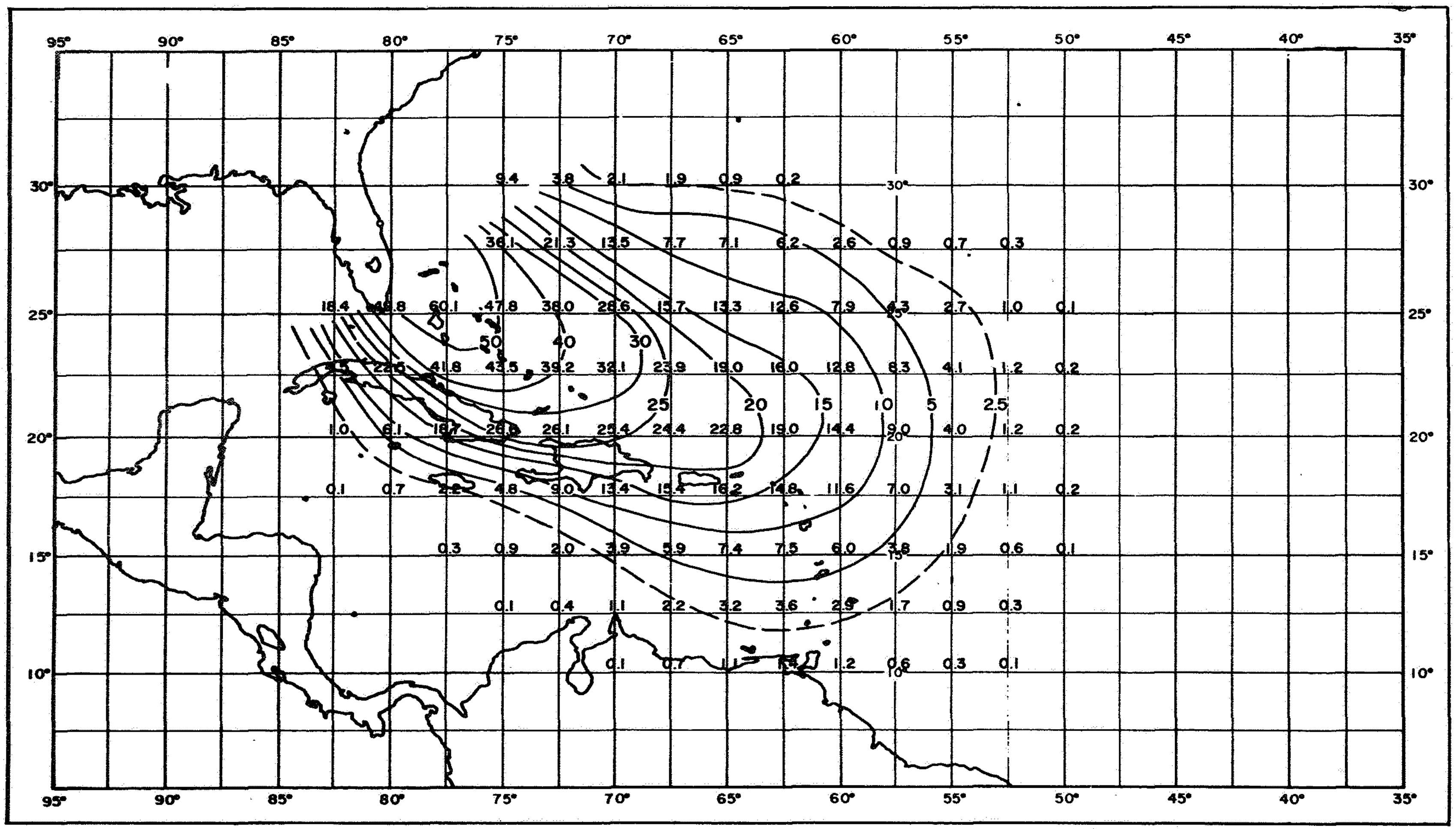


Figure 36: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through southeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 120 hours.

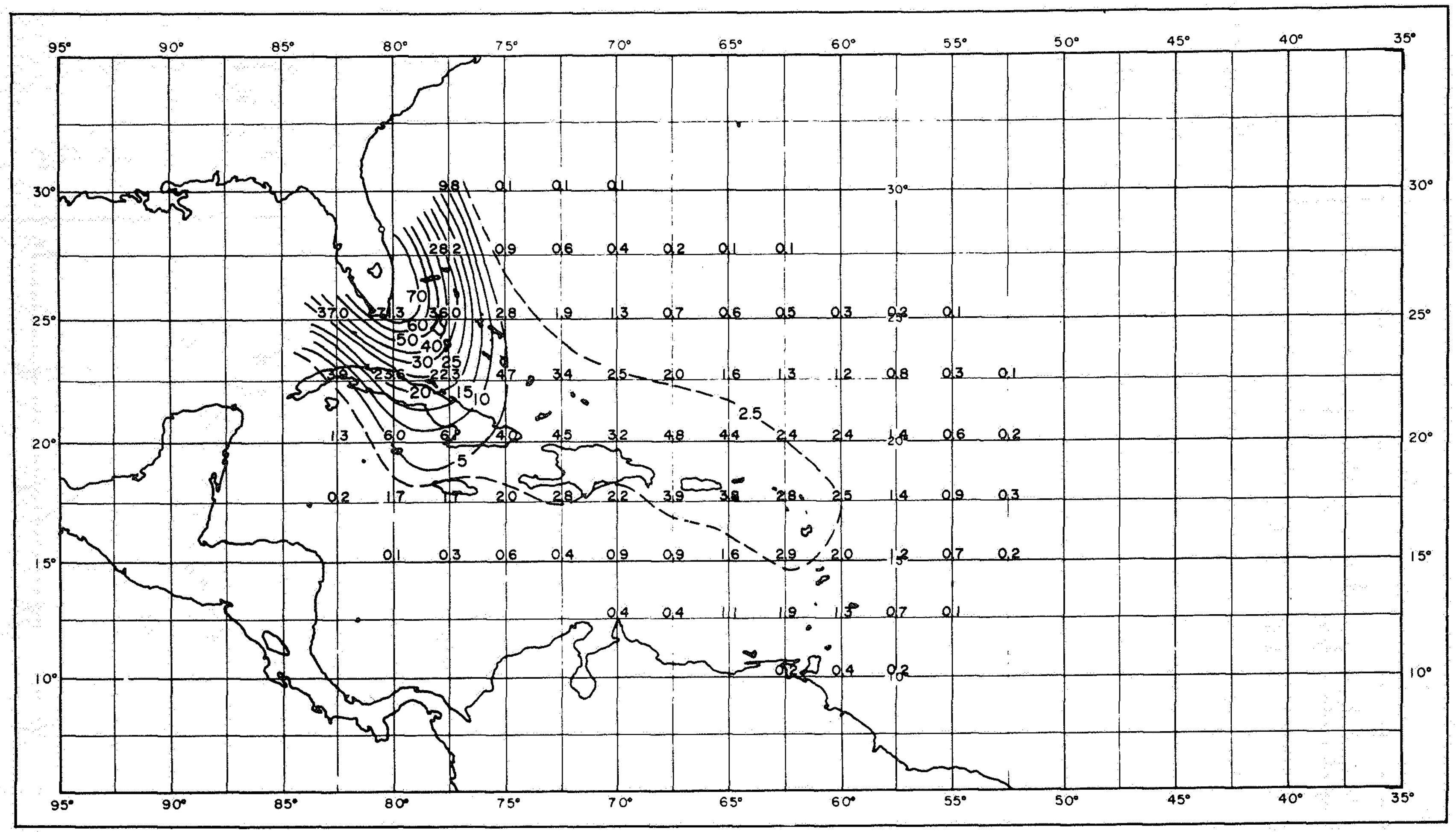


Figure 37: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the southeast through south and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 120 hours.

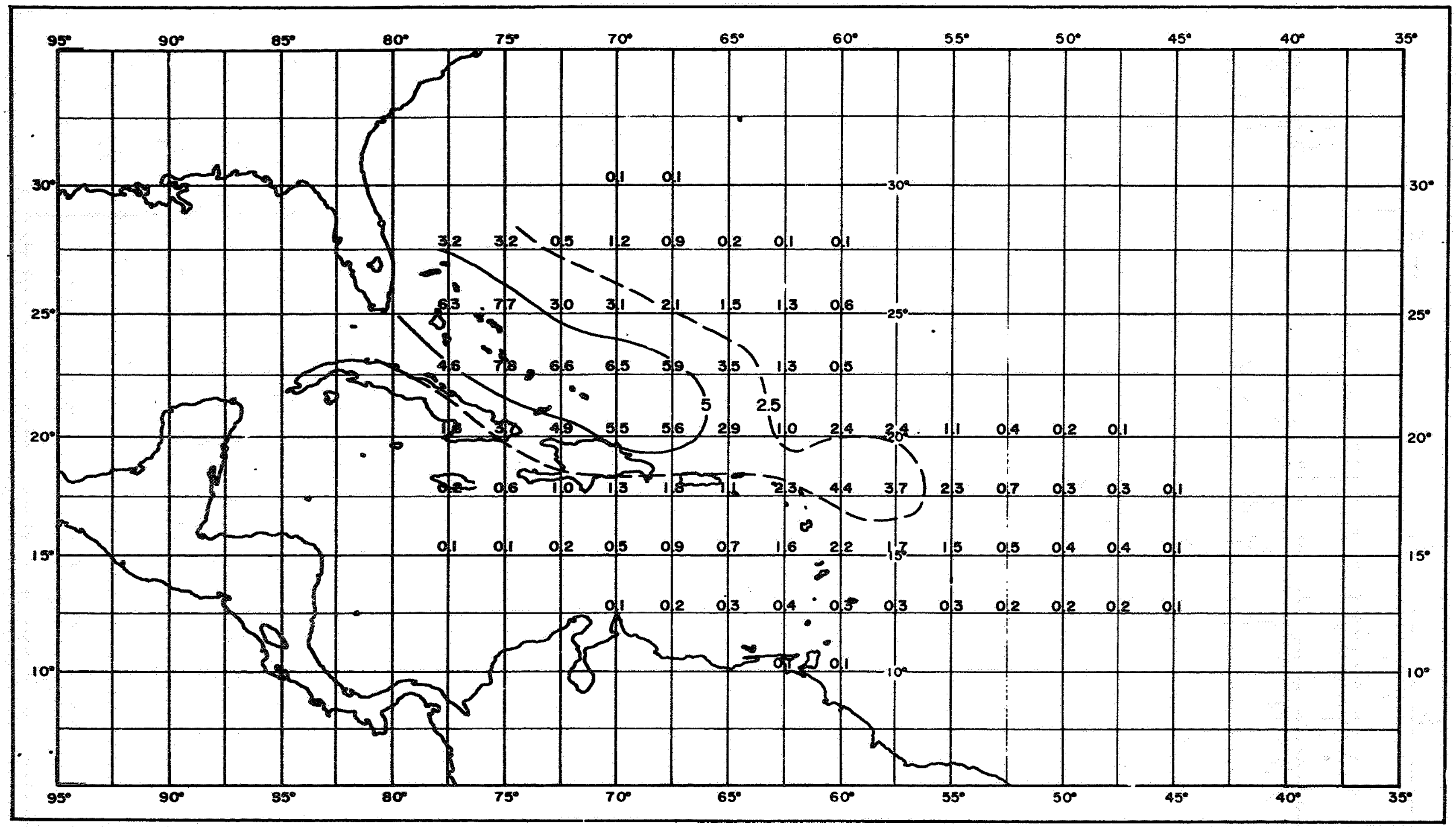


Figure 38: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through northeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 144 hours.

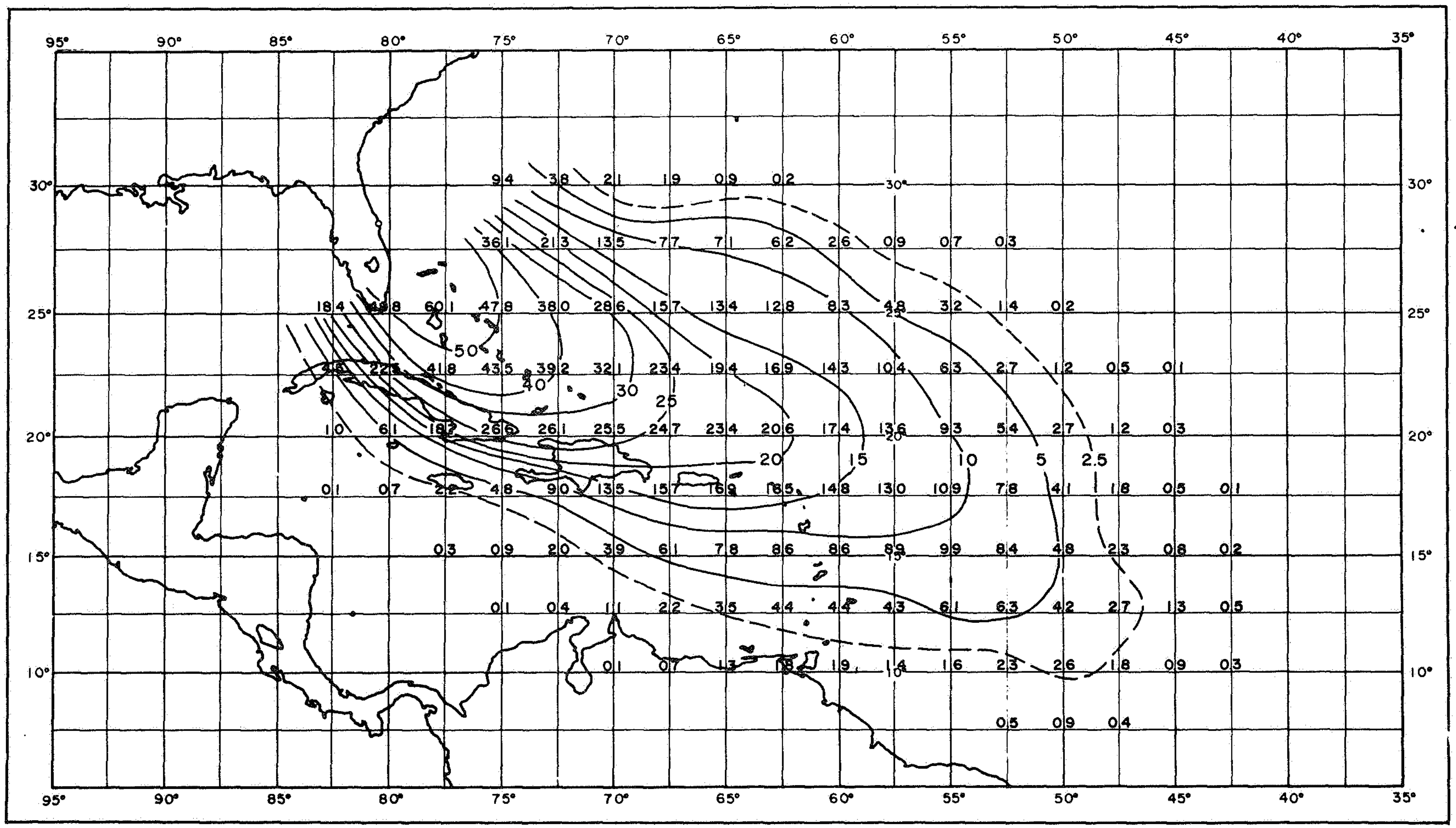


Figure 39: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through southeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 144 hours.

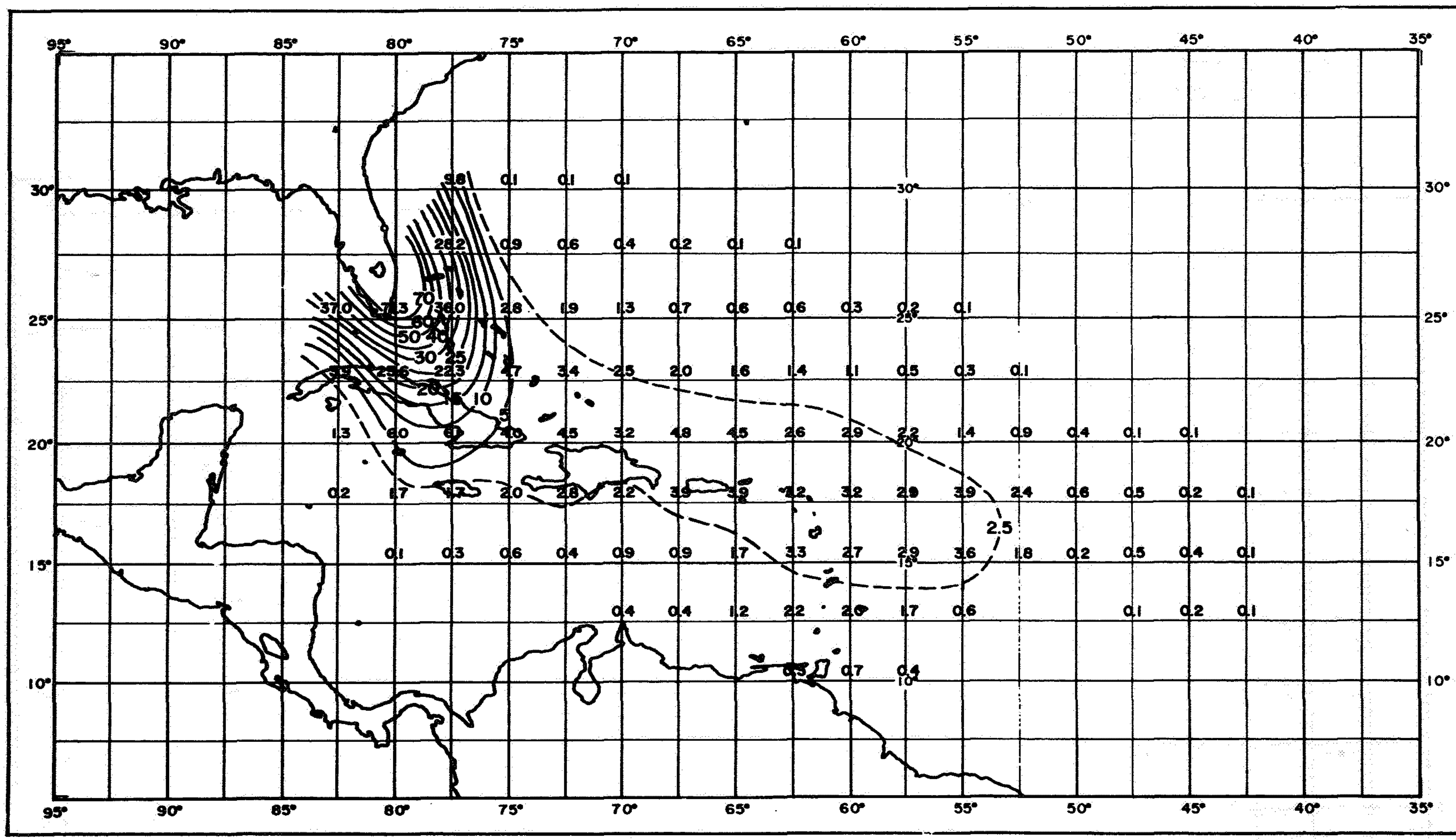


Figure 40: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the southeast through south and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 144 hours.

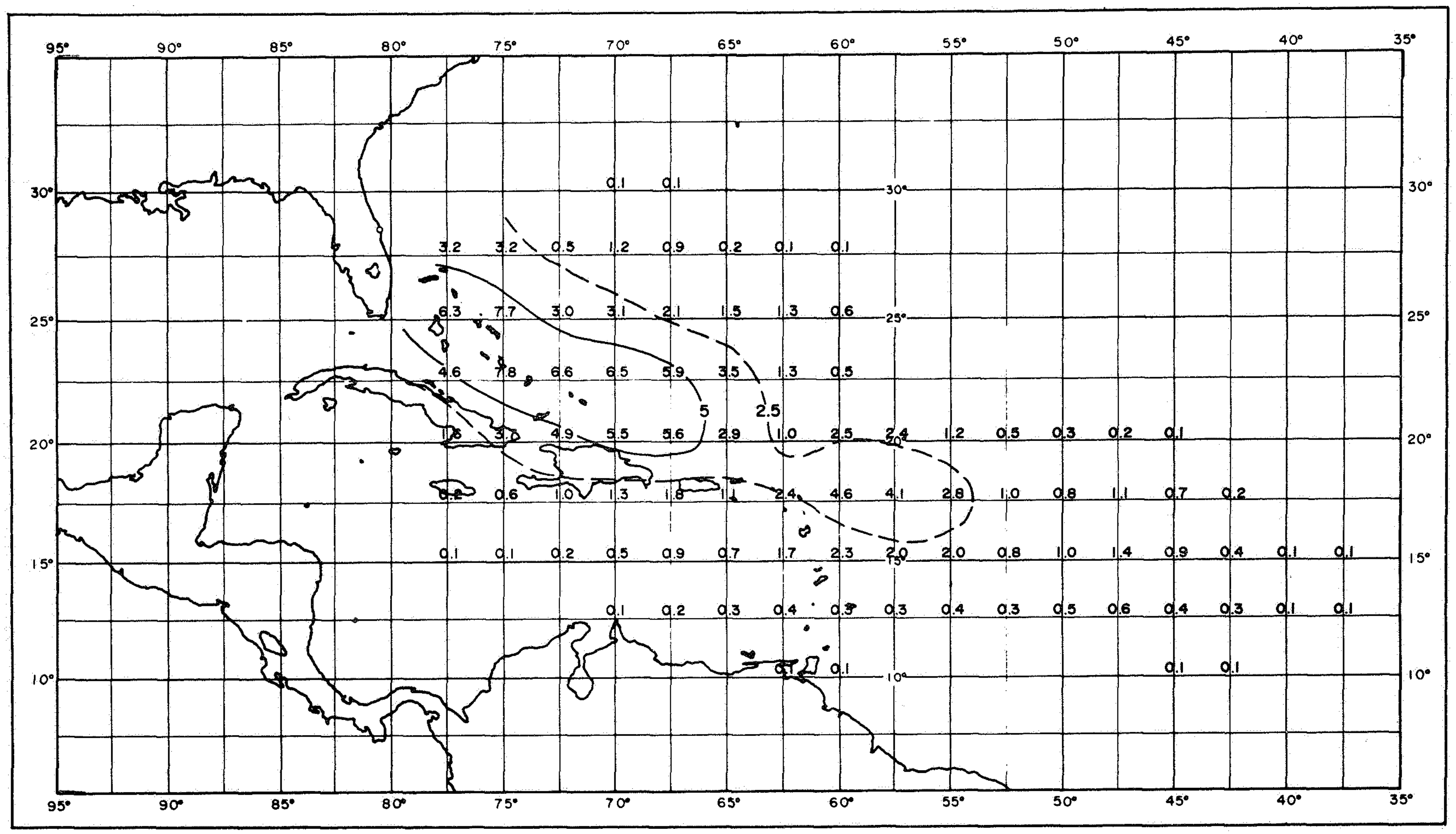


Figure 41: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through northeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 168 hours.

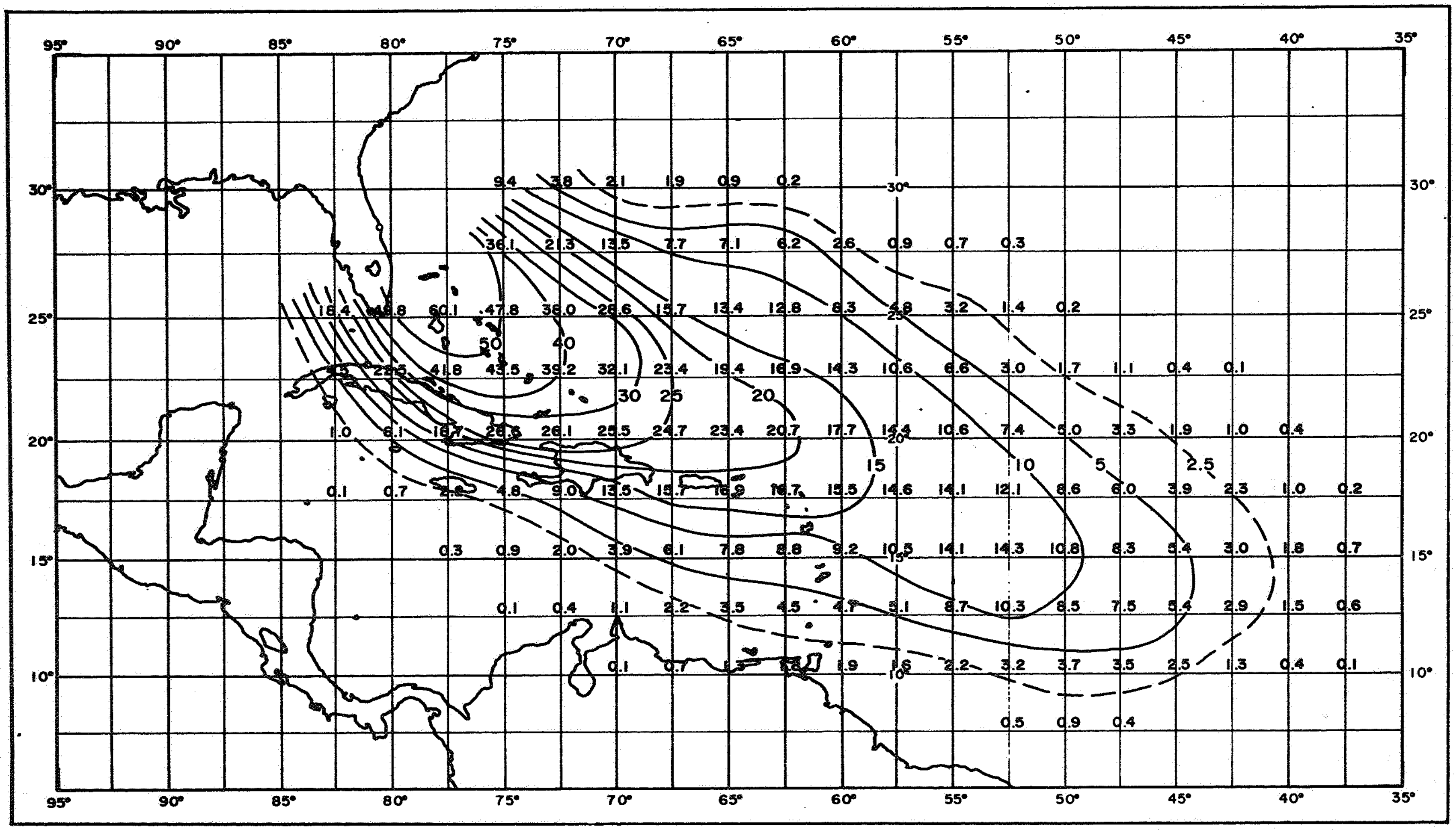


Figure 42: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the east through southeast and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 168 hours.

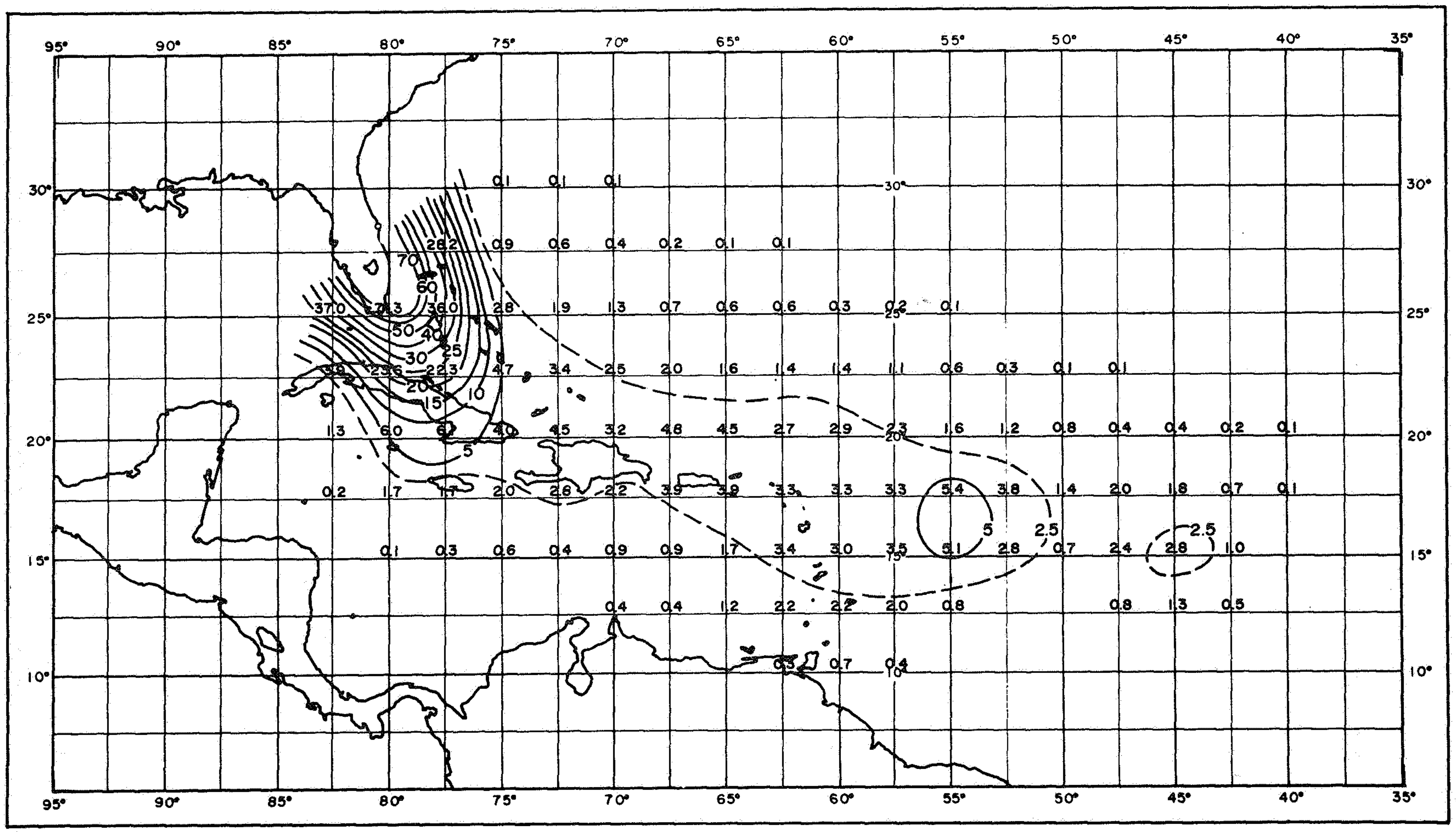


Figure 43: Cumulative percent probability of a tropical storm or hurricane, located at a given point, moving from the southeast through south and having originated in the eastern Caribbean or the Atlantic July 15 - October 31, producing critical winds at Cape Kennedy within 168 hours.

EXAMPLES ILLUSTRATING THE USE OF THE FIGURES AND TABLES

Example 1

What is the probability of critical winds occurring at Cape Kennedy (a) at least once during any given calendar year, and (b) twice during any given calendar year?

Discussion

From Table 4, it can be seen that the Poisson distribution function given by

$$p(x) = e^{-m}m^{x}/x! \tag{16}$$

where e is the base of natural logarithms, m is the sample mean and x is the number of occurrences per year, fits the observed frequencies quite well. The probability of critical winds occurring at least once in any calendar year is simply 1-p(0) or 1.00-0.64= 0.36 (36%). The probability of two storms occurring in one year is given directly by Table 4 as 0.06 or 6%. Use of the Poisson distribution assumes that the occurrence of critical winds is independent of other occurrences of this event.

Table 4. Observed and computed probability of yearly critical wind occurrences.

	OCCURRENCES PER YEAR			
	0	1	2	3
Observed frequency...........	0.63	0.30	0.07	0.00
Poisson probability..........	0.64	0.29	0.06	0.01

m=0.44

Example 2

Without regard to any current synoptic weather situation, what is the per cent probability of Cape Kennedy receiving critical winds from a tropical storm or a hurricane (a) during the month of September, (b) during the week of September 10-16, and (c) on September 25?

Discussion

The information is contained in Figures 5, 6 and 7. From Figure 5 based on past frequencies, critical winds can be expected during the month of September on 11.1% of the years. From Figure 6, critical winds can be expected during the week of September 10-16 on 4.8% of the years. From Figure 7, critical winds can be expected on September 25 on 0.47% of the years.

Example 3

A hurricane is located in the Atlantic near 16.2°N, 55.0°W at 1000GMT, September 15. Without considering this storm's direction of motion, what is the probability of producing critical winds at Cape Kennedy at any time within (a) 120 hours (5 days), and (b) 168 hours (7 days)?

Discussion

From Figure 27b, the 120-hour cumulative probability is read as 2.5% while from Figure 28b, the 168-hour cumulative probability is read as 14%.

Example 4

Given the same storm as in Example 3, what is the probability of receiving critical winds between the 120th and 168th hour; that is, between the 5th and 7th day?

Discussion

The procedure is to subtract the cumulative 120-hour probability from the cumulative 168-hour probability. In the above example, this would be 14% less 2.5%, or 11.5%. Specifically, 11.5% of the tropical cyclones located at 16.2°N, 55.0°W would be expected to produce critical winds at Cape Kennedy sometime between 1000GMT September 20 and 1000GMT September 22.

Example 5

Given storms located at (a) 25°N, 80°W, and at (b) 20°N, 55°W, what is the probability of Cape Kennedy observing critical winds from these storms at precisely 72 hours without regard to the storm's direction of motion?

Discussion

According to Figure 21a, both probabilities would be near zero. In the former case, if the storm were to strike Cape Kennedy, it would do so before 72 hours, while in the latter case it would do so after 72 hours.

Example 6

Given the same hurricane as in Example 3, what is the most likely time for this storm to produce critical winds at Cape Kennedy?

Discussion

An approximate estimate can be obtained from Figure 16. Construct a line through the storm position perpendicular to the centroid track and read about 148 hours.

A more precise method would be to use Figures 20 through 23. From Figures 20a, 20b and 21a, the probabilities at 24, 48 and 72 hours are all near zero. From Figure 21b, the 96-hour probability is near zero, from Figure 22a, the 120-hour probability is 0.5%, from Figure 22b, the 144-hour probability is 3.0%, and from Figure 23, the 168-hour probability is 1.8%. Graphically, this can be represented as shown in Figure 44. The maximum probability of slightly over 3% is seen to occur at about 142 hours.

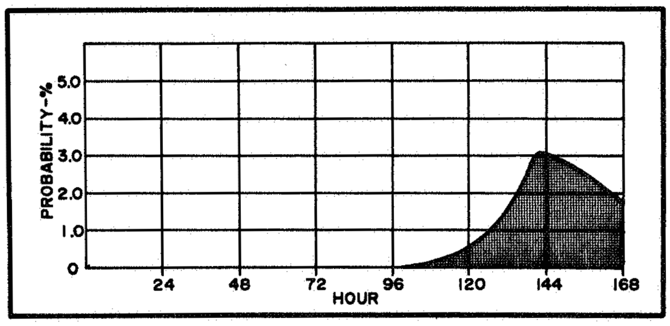


Figure 44:
Probability of a tropical stor or hurricane located at 16.2N, 55.0W, producing critical wind at Cape Kennedy at specified hours.

Example 7

What is the average translational speed of a hurricane or tropical storm which may affect Cape Kennedy?

Discussion

The average speed varies depending on both the distance from Cape Kennedy and the source region of the storm. The average speeds can be calculated from Figure 16. These are listed in tabular form in Table 5a and Table 5b.

Example 8

A hurricane is located in the Atlantic near 15°N, 49°W, and is moving in a west-northwesterly direction. What is the probability of this hurricane producing critical winds at Cape Kennedy within 168 hours?

Discussion

From Figure 42, the probability is read as 10%.

Example 9

A hurricane is located in the Atlantic near 20°N, 65°W and is moving directly toward the northwest. What is the probability of this hurricane producing critical winds at Cape Kennedy within 144 hours?

Discussion

Since this storm is moving from a direction which is represented both by Figure 39 and Figure 40, the recommended procedure would be to take a mean of the values obtained from each of the two figures. Figure 39 gives a probability of 23% while Figure 40 gives a probability of 5%. The desired probability is therefore 14%.

Table 5a: Average translational speeds of tropical cyclones which have produced critical winds at Cape Kennedy - Storms originating in Atlantic or eastern Caribbean

From (hr)	To (hr)	Distance Between Centroids (NM)	Average Speed (Knots)
0	24	195	8.1
24	48	230	9.6
48	72	270	11.3
72	96	260	10.8
96	120	240	10.0
120	144	300	12.5
144	168	310	12.9
0	168	1805	10.7

Table 5b: Average translational speeds of tropical cyclones which have produced critical winds at Cape Kennedy - Storms originating in the western Caribbean or Gulf of Mexico

From (hr)	To (hr)	Distance Between Centroids (NM)	Average Speed (Knots)
0	24	260	10.8
24	48	160	6.7
48	72	100	4.1
72	96	190	7.9
96	120	70	2.9
0	120	780	6.5

CONCLUSIONS

The probabilities computed in this study are most useful for time scales beyond those for which forecasts are issued. Normally military and NASA installations will have forecasts available for periods extending out to 72 hours. Studies have been made on the accuracy of these forecasts, and some use the forecasts themselves to compute storm strike probabilities. Among these are Tracy (1966), Appleman (1963), U.S. Navy Weather Research Facility (1963), and Veigas et al (1959). Although climatological probabilities for periods less than 72 hours are presented in this paper, they are not intended to replace those based on the latest available forecasts.

There were insufficient data available to process May, June or early July storms according to the method outlined. However, if a storm should appear during this period, an estimate of the probability of its affecting Cape Kennedy can be obtained by noting its point of origin. For example, if a May, June or early July storm originated in the western Caribbean or the Gulf of Mexico, the probabilities computed for the late-season storms would be more appropriate. Similarly, if a storm appears in the Atlantic or eastern Caribbean during the early season, probabilities computed for the mid-season storms would be used. In either case, caution should be used since the computations were not made from early-season data.

Certainly more confidence can be placed in the probabilities computed for mid-season storms, that is, those originating in the Atlantic or the eastern Caribbean, than for late season storms because there were more data available from which to compute the former. Indeed, it was not possible to stratify the latter group of storms according to antecedent motion due to lack of sufficient data.

It is believed that the probabilities computed herein will be of use to planners whose responsibility it is to initiate action far in advance of the time of onset of critical winds. Besides giving an estimate of the probability and time of Cape Kennedy being affected by a tropical cyclone, the study clearly shows the areas from which the greatest threats emanate as well as those areas from which there is little likelihood that a storm may reach Cape Kennedy.

The breakdown of tropical storm occurrences in the Atlantic, Gulf of Mexico and the Caribbean into $2\frac{1}{2}$ degree latitude-longitude boxes is a refinement of tropical cyclone climatology since previous studies have shown the distribution over 5 degree latitude-longitude boxes.

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APPENDIX

Computation of B in Formula (11)

$$P' = BN/N_t, \; BN \leq N_t, \; N_t > 0$$

Consider the 120-hour (5-day) ellipses for storms originating in the Atlantic or eastern Caribbean (Figure A).

Now consider the 2½ degree latitude-longitude box bounded by 20N, 62.5W, 17.5N, and 65W.

Portions of the .50-.70, .30-.50, and .10-.30 elliptical rings pass through the box. Each elliptical ring contributes .20 (20 per cent) to the total ellipse.

The contribution of the area in the box to the entire ellipse in terms of probability can be approximated by finding the portion of each complete elliptical ring that is included in the box. For this a planimeter or a fine-mesh grid can be used. The latter was used in this study. In this case, the box includes:

5.0 per cent of the .50-.70 elliptical ring

8.8 per cent of the .30-.50 elliptical ring

14.5 per cent of the .10-.30 elliptical ring

To approximate the portion of the ellipse contained in the box, multiply the portion of each elliptical ring included in the box by the per cent contribution of each elliptical ring to the entire ellipse, and total the products.

5.0% x .20 = 1.0%

8.5% x .20 = 1.7%

14.5% x .20 = 2.9%

Total included in box 5.6%

That is, 5.6% of the storms within the ellipse would have been in this particular box assuming a bivariate normal distribution. Since there were 16 storms from which the ellipse was computed at 120 hours, the total in the box would have been

$$B = 5.6\% \times 16 = .89 \text{ storms}$$

There are precise methods available for integrating the bivariate normal elliptical density function over an offset circle. Extensive tables of values so obtained have been published; the latest and most complete of which have come to the attention of the authors is by Groenewoud, Hoaglin, Vitalis, and Crutcher (1967). A comparison of results with those obtained by the method described in this paper showed close agreement. For example, in the case cited above, 5.8% was obtained for B using an equivalent area offset circle centered at the center of the latitude-longitude box, compared to the 5.6% approximation obtained using the fine-mesh grid.

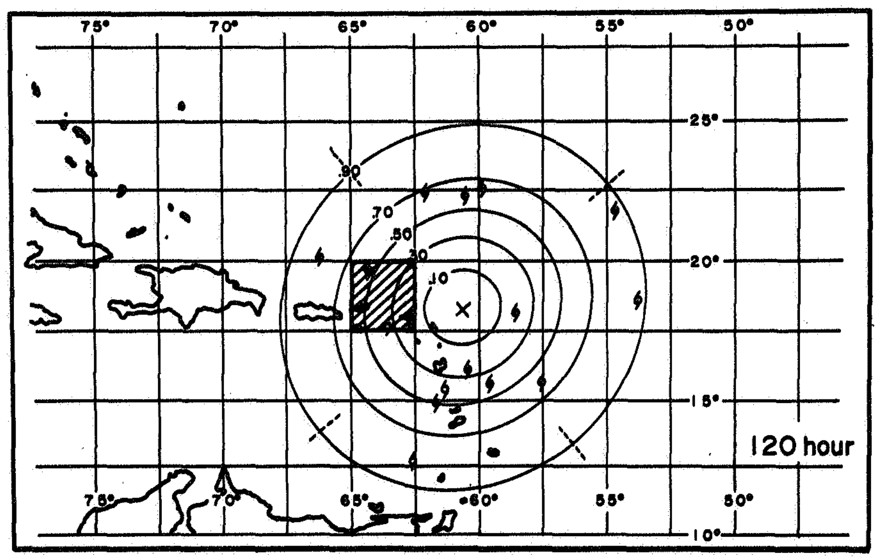

Figure A: Ellipse used in illustration of the computation of B in formula (11), $P' = BN/N_t$